Final Report to
NASA-KSC
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Shuttle Transportation System Meteorological Expert — STSMET

Thunderstorm Weather Forecasting Expert System — TWFES

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ADL/NASA Thunderstorm Weather Forecasting Expert System

TWFES

Executive Summary

In May 1984, NASA approved a three-year project to develop a weather forecasting system to support Shuttle operations. Arthur D. Little, Inc. (ADL) was selected in April 1985 to undertake this project. The results of a feasibility study (completed December 1985) indicated that a two-year effort be undertaken to construct a prototype thunderstorm weather forecasting expert system (TWFES). Work was divided into two one-year phases, each to be concluded by a presentation and review. Phase One was completed in September 1986, and a report on that research was presented. The second phase was completed in September 1987. This summary describes the work and findings of that phase.

Introduction:

Traditional meso-scale forecasting seeks to understand weather as a fluid dynamics problem. A mathematical model of the atmosphere as a collection of "particles" together with observations of the current state, and all pertinent effectors, should enable one to predict all future states over time. This approach is fundamentally limited by the minimum size of the "particles". This minimum size governs the accuracy of data collection and computational tractability of a simulation. The scales required for useful forecasting at the Cape are prohibitively small.

Human experts who forecast Cape weather seem to rely on qualitative modeling of local atmospheric systems, and empirical correlation of daily observations. Implicit in both is the idea of cause and effect over time. Interviews with meteorologists suggest that they reason about the weather in terms of <u>template days</u>, and fine tune their predictions based on comparisons of observations and results from previous days. Template days are constructed using a combination of meso-scale knowledge and qualitative physical reasoning. It appears that experts can classify all weather phenomenon within a small number of template days (10- 20).

TWFES is an attempt to use symbolic processing to capture a simplified version of human reasoning about weather forecasting. TWFES represents each template day as a "<u>scenario</u>". Each scenario is composed of any number of "events". These events are linked together in a tree structure, much like a flowchart, that admits only certain legal event sequences. Events can also be constrained to occur within a time window, either absolute or with reference to the previous event. Each event has a "predicate" which determines whether the event has happened. The predicate is a function written in Lisp which is able to access any "data source." A data source is either a physical object which is of interest to the forecaster, or a station that records observations. For example, a particular cloud may be a data source. The TWFES forecasting process may be thought of as follows:

- Update all machine readable data sources.
- Traverse the tree structure of each scenario to identify the current event of interest.
- Determine (by evaluation of the event predicate) whether the event has taken place (this step may require asking the user for information about a data source).
- Present information about active scenarios.
- Repeat as long as any scenario is active.

The scenario reasoning structure of TWFES is unique among systems which do logical inference. An event in TWFES has many similarities to a rule in a traditional rule-based expert system. A traditional system, however, does not provide any mechanism to establish a time window for each rule. TWFES provide a convenient and intuitive mechanism in the form of a graphic "scenario editor."

System Architecture:

TWFES Phase Two represents a substantial upgrade and integration of Phase One. The original inference engine, the automated reasoning tool (ART) from Inference Corporation has been removed. It became clear after Phase One that ART was inadequate from the perspectives of real-time performance, integration of TWFES subsystems and software maintenance. The current TWFES consists of three tightly coupled modules: A scenario editor, and two runtime-user interface modules--one to display map-oriented graphics, the other to display scenario status information. The scenario status interface also allows the user to control "TWFES time", to recall data for a "saved day", and to control the real-time data acquisition interface to MIDDS.

The scenario editor was redesigned to improve the display of the events compromising a scenario. The sequence of events is represented as a tree where each node is either an event or a branch. Branches can be of two types AND or OR. The runtime system is capable of correctly interpreting any legal AND-OR tree. The scenario editor-user interface is quite flexible, yet the commands it provides the user make it impossible to construct a tree which the machine cannot interpret.

The runtime system consists of a special scenario processor similar to, but much faster than ART. In addition, the scenario processor operates directly on the structure created by the scenario editor, eliminating any need to convert scenarios to ART syntax. Current benchmarks indicate that the system can handle about 100 active scenarios in real time. Most experts feel that 10 to 30 should be sufficient for a given season. When TWFES is not running in real-time, the user has elaborate control over the manner in which the system allows time to pass. The user may slow time, stop it, and even go back in time (to change observations).

TWFES Phase Two provides an integrated data management system organized around the concept of a "day." When a user "saves a day", TWFES stores (as a set of files) all information available about weather observtions for that day. The user may later re-load this day and re-run TWFES for simulation, study, or training purposes.

Currently, TWFES is able to automatically access MIDDS and download large amounts of machine readable data which represent observations. This data acquisition process should be offloaded onto a PC/AT class machine, so that the symbolic processing power of the Lisp machine can be focused on reasoning about scenarios.

Software Maintenance and Technology Transfer

TWFES is written in Zetalisp (using common Lisp where possible), and is organized as a standard Zetalisp system (defsystem) allowing easy software maintenance and distribution. ADL has delivered a complete knowledge modeling and system design course which, together with videotapes of selected system and software demonstrations, fulfills the technology transfer requirements of NASA.

TWFES Phase One was used throughout the summer, within the (CIF), as a tool to help understand Cape weather. A daily log of weather observations was maintained, and a detailed study of scenarios, specifically in-situ rain and thunder was performed. The results of this study can be used to strengthen and refine the current scenario-processing algorithm. It appears that the results of this study can be used to strengthen and refine the current scenario-processing algorithm. It appears that the results of this study fit nicely within a model of scenario classification proposed by Roger Pielke.

Recommendations for Future Development:

The Department of the Air Force has indicated at least four applications for TWFES at the Cape Canaveral Forecast Facility (CCFF). Integration of TWFES into the CCFF would require specification of a man/machine interface suitable to the needs of the forecast facility staff. Real-time data collection for TWFES should be performed by a dedicated PC/AT class computer, interfaced directly to input from observation stations. Successful resolution of each of these issues requires the close cooperation and guidance of the CCFF staff. With sufficient assistance from the Air Force, TWFES will evolve into a valuable training and forecasting tool.

Powerful Concept

Scenario-based reasoning is a unique and powerful concept which extends the capability of traditional rule-based expert system. It has proven quite useful in the understanding and simulation of the complex problem of weather forecasting. It should provide similar expressive power when applied to other domains in which explicit temporal reasoning is required. Examples include: task scheduling and control, and simulation of physical processes.

PROJECT INTRODUCTION

HISTORY OF THE PROJECT

JANUARY	1985	RFP OUT FOR FEASIBILITY STUDY
APRIL	1985	A. D. LITTLE, INC. SELECTED FOR FEASIBILITY STUDY
DECEMBER	1985	ADL FINAL REPORT RECOMMENDS TWFES
APRIL	1986	TWO YEAR CONTRACT WITH ADL
SEPTEMBER	1986	DEMONSTRATION PROTOTYPE (PHASE I) COMPLETED
JANUARY	1987	RESEARCH PROTOTYPE (PHASE II) BEGINS
SEPTEMBER	1987	RESEARCH PROTOTYPE COMPLETED

THE A. D. LITTLE RESEARCH TEAM

JEFF SMEDLEY	Low Altitude Dynamics
DAVE HELMS	University of Louisiana
ROGER PIELKE	Colorado State University
STEVE GANDER	Odyssey Systems
BOB McARTHUR	Albathion Software
FRANCOIS GADENNE	Arthur D. Little

PROJECT REVIEW

SUMMERTIME THUNDERSTORM FORECASTING AT KSC

METEOROLOGICAL PROBLEM DESCRIPTION

- TROPICAL

- DIURNAL CYCLE

- STRONG LAND-SEA EFFECTS
  - -- SEA BREEZE BOUNDARY
  - -- CAPE GEOGRAPHY

- SMALL DAY-TO-DAY VARIATIONS

- QUICKLY DEVELOPING RW AND TRW

SUMMERTIME THUNDERSTORM FORECASTING AT KSC

OPERATIONAL PROBLEM DESCRIPTION

- LEAD-TIME: 30 MINUTES TO 2 HOURS
- SEVERAL DOZEN WEATHER SENSITIVE TASKS
- PHENOMENA OF INTEREST: LIGHTNING, RW
- USE OF COMPLEX, SOPHISTICATED COMPUTER SYSTEMS (MIDDS)
- CONSTANT INTERRUPTIONS
- SHIFT CHANGE AT TIME OF MAXIMUM CONVECTION

SUMMERTIME THUNDERSTORM FORECASTING AT KSC

ANALYTICAL PROBLEM DESCRIPTION

- VERY HIGH DATA RATES

- NUMEROUS TYPES OF DATA AVAILABLE
  - STANDARD
  - EXPERIMENTAL

- EXCELLENT DATA DISPLAY

- LITTLE OBJECTIVE GUIDANCE

- VISUAL OBSERVATION LARGELY UNAVAILABLE

BACKGROUND

FEASIBILITY STUDY

- SUMMERTIME THUNDERSTORM NOWCASTING OFFERS THE GREATEST POTENTIAL FOR APPLYING AI TECHNIQUES AT CCFF.

- A SIGNIFICANT ASPECT OF FORECASTER EXPERTISE IS THE ABILITY TO RETAIN, DEVELOP AND USE "SCENARIOS" WHICH CORRESPOND TO PAST WEATHER EXPERIENCES.

- IT IS POSSIBLE TO CAPTURE AND REPRESENT THIS EXPERTISE USING COMMERCIALLY AVAILABLE AI TECHNOLOGY.

- A REPRESENTATION SCHEME AND CONTROL STRUCTURE WAS PROPOSED WHICH MIMICS FORECASTERS' REPRESENTATION AND USE OF WEATHER SCENARIOS.

PHASE I OBJECTIVES:

DEMONSTRATION PROTOTYPE

CONDUCT THE FIRST ROUND OF KNOWLEDGE ENGINEERING TO DETERMINE IF THE SCENARIO REPRESENTATION WAS ADEQUATE TO EXPRESS THE TWO EXPERT FORECASTERS' KNOWLEDGE ;

BUILD A CUSTOM EDITOR FOR THE FORECASTERS TO USE TO ENTER THEIR OWN EXPERTISE INTO THE SYSTEM ;

DEVELOP SKELETAL VERSIONS OF THE SEVEN PROPOSED RUN-TIME CONTROL MODULES ;

BUILD A RUDIMENTARY DATA INTERFACE TO MIDDS SYSTEM ;

EVALUATE THE ADEQUACY OF THE APPLIED REASONING TOOL (ART) AS A TWFES DEVELOPMENT ENVIRONMENT.

PHASE I MAJOR FINDINGS

- SCENARIO REPRESENTATION SCHEME IS A GOOD FIT TO NOWCASTING EXPERTISE

- NO MAJOR CHANGES REQUIRED IN PROPOSED ARCHITECTURE

- APPLIED REASONING TOOL (ART) EVALUATION:

    -- COST-EFFECTIVE DEVELOPMENT ENVIRONMENT

    -- TOO INEFFICIENT FOR OPERATIONAL TWFES

SUMMARY OF PHASE I RESULTS

TOPIC	GOALS	ACCOMPLISHMENTS
SCENARIO CAPTURE	1. SEVERAL IN SITU THUNDER	1. 11 SUMMER THUNDER 2. 1 WINTER THUNDER 3. 25 HOURS DEBRIEFING TAPES 4. 200 PAGES TRANSCRIPTS
SCENARIO EDITOR	1. SIMPLE STRUCTURE EDITOR	1. STRUCTURE EDITOR 2. STRONG USER INTERFACE 3. SCENARIO DEPENDENCY GRAPH 4. FEATURE ICONOGRAPHY 5. ANIMATED MAP FOR EVENTS

SUMMARY OF PHASE I RESULTS

TOPIC	GOALS	ACCOMPLISHMENTS
RUN-TIME SYSTEM	1. PROCESS SINGLE SCENARIO 2. SEVEN CONTROL MODULES	1. PROCESS MULTIPLE SCENARIOS 2. CUSTOM WFES INFERENCE ENGINE 3. DYNAMIC STATUS GRAPH 4. DYNAMIC MAP
DATA INTERFACES	1. SERIAL LINK 2. ONE SCALAR DATA STREAM	1. DOWNLOAD MIDDS TTY OUTPUT 2. UPPER-AIR SOUNDINGS, SURROUNDING STATIONS

DETAILED FINDINGS OF PHASE I

SCENARIO REPRESENTATION

- SCENARIOS WORK WELL FOR SUMMER THUNDER.
- SCENARIOS APPEAR APPROPRIATE FOR MOST OTHER WEATHER PHENOMENA OF OPERATIONAL INTEREST.
- TWFES PROVIDES:
  - STRUCTURING FACILITY
  - MEMORY ENHANCEMENT
  - TESTABILITY
- WORKING WITHIN THE SCENARIO STRUCTURE HAS CHANGED FORECASTER THINKING:
  - ANALYSIS ROUTINE
  - HYPOTHESIS STRUCTURING
  - MEASUREMENT REQUIREMENTS
- MORE DIFFICULT THAN ANTICIPATED TO TEACH A STRUCTURED WAY OF THINKING.

DETAILED FINDINGS OF PHASE I

PROPOSED ARTHICTECTURE

- EMPHASIS ON TEMPORAL SEQUENCING WAS CRUCIAL.
- OBJECT HIERARCHY WAS VERY APPROPRIATE AFTER SLIGHT EXTENSION.
- MIXTURE OF QUALITATIVE OBSERVATIONS WITH QUANTITATIVE ANALYSIS WAS ABSOLUTELY NECESSARY.
- EXTENSION TO AUTOMATIC PATTERN RECOGNITION IS STRAIGHTFORWARD (IF ALGORITHMS EXIST).
- AN "INTELLIGENT" MAPPING FACILITY IS A KEY PART OF OPERATIONAL SUCCESS.

NUMERICAL MODELS VS. TWFES

Characteristics	Models	TWFES
REASONING	DEDUCTIVE	INDUCTIVE
INPUT	FIXED	MULTIPLE, DYNAMIC
PRODUCTS	QUANTITATIVE	QUANTITATIVE, QUALITATIVE
ASSUMPTIONS	FIXED, IMPLICIT	FLEXIBLE, EXPLICIT
TIME-INTERVALS	PRE-DETERMINED	CONTINUOUS
EXPLANATION	NONE	DETAILED, MULTI-LEVEL

PHASE II OBJECTIVES:

RESEARCH PROTOTYPE

IMPROVE THE PERFORMANCE AND THE MAINTAINABILITY OF BOTH THE SCENARIO EDITOR AND THE RUN-TIME SYSTEM ;

DEVELOP AN AUTOMATED DATA INTERFACE TO MIDDS SYSTEM ;

CONTINUE TO THE ACQUISITION OF THE METEOROLOGICAL KNOWLEDGE USING THE SCENARIO EDITOR ;

EXPLORE THE POSSIBLE USES OF THE SCENARIO-BASED REASONING TECHNOLOGY

SUMMARY OF PHASE II RESULTS

Topic	Goal	Accomplishments
SOFTWARE DEVELOPMENT	IMPROVE PERFORMANCE	- CURRENT TWFES RUNS 100 TIMES FASTER THAN THE DEMONSTRATION PROTOTYPE
		- RESEARCH PROTOTYPE CAN HANDLE VERY LARGE NUMBER (50-100) OF SCENARIOS SIMULTANEOUSLY
		- MAP GRPAHICS VASTLY IMPROVED
		- INTEGRATION OF SCENARIO EDITOR INTO THE RUN-TIME TWFES
	IMPROVE MAINTAINABILITY	- TRANSLATION FROM A.R.T. TO LISP
		- MODULAR REDESIGN OF THE SOFTWARE ARCHITECTURE
		-USE OF COMMON LISP WHERE POSSIBLE
		- VIDEO AND PERSONAL TRANSFER OF KNOWLEDGE FOR USE OF TWFES
	DEVELOP MIDDS INTERFACE	- ABILITY TO PROCESS ALL MIDDS SCALAR DATA OTHER THAN FIELD MILLS
		- AUTO-DIAL-UP FOR DOWNLOADING
		- AUTOMATED TRANSLATION OF MIDDS SCALAR DATA INTO TWFES DATA STRUCTURES

SUMMARY OF PHASE II RESULTS

(CONTINUED)

Topic	Goal	Accomplishments
METEO-ROLOGICAL KNOWLEDGE	CONTINUE KNOWLEDGE ACQUISITION	- DAILY LOG OF WEATHER OBSERVATIONS (SUMMER 87) - DETAILED STUDY OF IN-SITU SCENARIOS - CLASSIFICATION SCHEME FOR IDENTIFYING APPROPRIATE SCENARIOS
	TRANSFER KNOWLEDGE MODELING APPROACHES	- DELIVERED COMPLETE KNOWLEDGE MODELING AND SYSTEM DESIGN COURSE - DOCUMENTATION OF GENERALIZED PROCEDURES FOR KNOWLEDGE ACQUISITION AND REFINEMENT
SCENARIO BASED TECHNOLOGY	EXPLORE ADDITIONAL APPLICATIONS	- DOCUMENTATION OF OTHER USES FOR THE TWFES TECHNOLOGY

SUMMERTIME THUNDERSTORM FORECASTING AT KSC

TWFES BENEFITS

- PERMANENT CAPTURE OF NOWCASTING EXPERTISE

- INTEGRATION OF MULTIPLE DATA SETS

- DAILY MEMORY FOR FORECASTING CREW

- AT RUN-TIME, IT ALSO PROVIDES:

  -- MOST SIGNIFICANT PHENOMENA AND FEATURES EXPECTED DURING THE NEXT 1 TO 3 HOURS

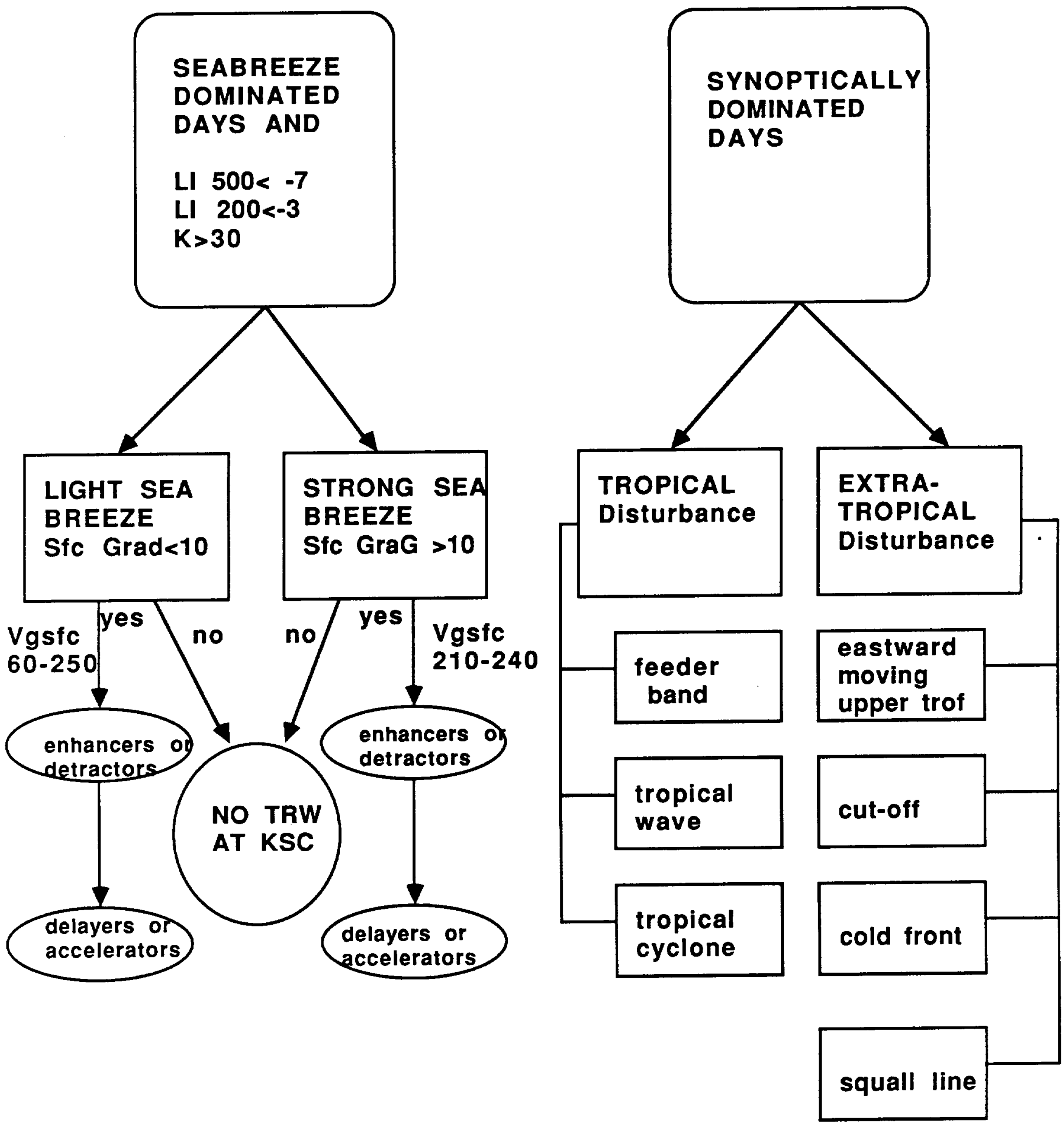
  --DATA SOURCES OF INTEREST

  -- ANALYSIS (AUTOMATIC GUIDANCE) TO IDENTIFY SIGNIFICANT FEATURES USING SPECIFIED DATA

  -- "TYPICAL" WEATHER BEHAVIOR BASED UPON PAST EXPERIENCE

SCENARIO TAXONOMY

CLASSIFICATION LOGIC



MODIFICATION TO SEA BREEZE DOMINATED DAYS

A. ENHANCER	**DETRACTOR**
-STRONG 700 mb JET (>20 K)	850 mb and: lower wet, dry above
-Tc >88F	
- LI 500 <-9	
B. ACCELERATOR	**DELAYER**
- Stationary upper lever trof to west	- Tc>86F
- Observed cumulus cloud streets	-Anticyclone shear to 500 mb

key: *enhancer* <u>*detractor*</u>

accelerator <u>delayer</u>

I. SEA BREEZE DOMINATED DAYS

(NO EXTENSIVE CIRRUS,
NO ORGANIZED SYNOPTIC
CLOUD CLUSTERS)

A. LIGHT SEA BREEZE (Sfc Gradient < 10 knots)

1. LI 500<-7, K>30
LI200 <-3

Stationary (SBST1) → a) SW through SSE,
Tc<83F
Lt. winds at 700 mb

Jet line (SBST2) → b) SE through SW, (>20 knots), 310-340, Tc <83F *with strong 700mb jet (>20 knots)*

Rain shower (SBST5) → c) 060-140, Tc< 86F <u>*with 850 mb, lower wet, above dry*</u>

Late Thunder (SBST3) → d) <u>Anticyclonic shear Sfc to 100 mb</u>

Vsfcgrad. 210-230, 5 to 12 knots
LI 500<-9

Late severe (SBST1/SBST3) → e) *Tc>88F, LI500<-9*

LI200<-3,
5 knots<Vgrad<15 knots
from 210-250

2. Other situations without thunderstorms

enhancer	detractor
accelerator	delayer

I. SEA BREEZE DOMINATED DAYS (CONTINUED)

(NO EXTENSIVE CIRRUS,
NO ORGANIZED SYNOPTIC
CLOUD CLUSTERS)

A. STRONG SEA BREEZE (Sfc Gradient > 10 knots)

1. LI 500<-7, K>30
LI200 <-3

Linear Boundry → a) Vgrad. sfc : 210-240<25 knots
Tc <83F

Late Thunder → b) Same as a), except Tc >86F

SBLB3 → c) Same as a) except anticyclonic shear to 500 mb

SBLSB4 → d) Same as c) except stationary trof to west

SBLB5 → e) Same as a) except LI<-9

f) Observed cumulus cloud streets, anticyclonic sfc ridge with radius of curvature near KSC <100 miles

II. SYNOPTICALLY DOMINATED DAYS

A. COLD FRONTAL

B. SQUALL LINE AHEAD OF COLD FRONT

C. CUT-OFF

a) Lt. Sfc. winds, cut-off offshore

b) Strong winds aloft, very cold aloft,
cut-off offshore

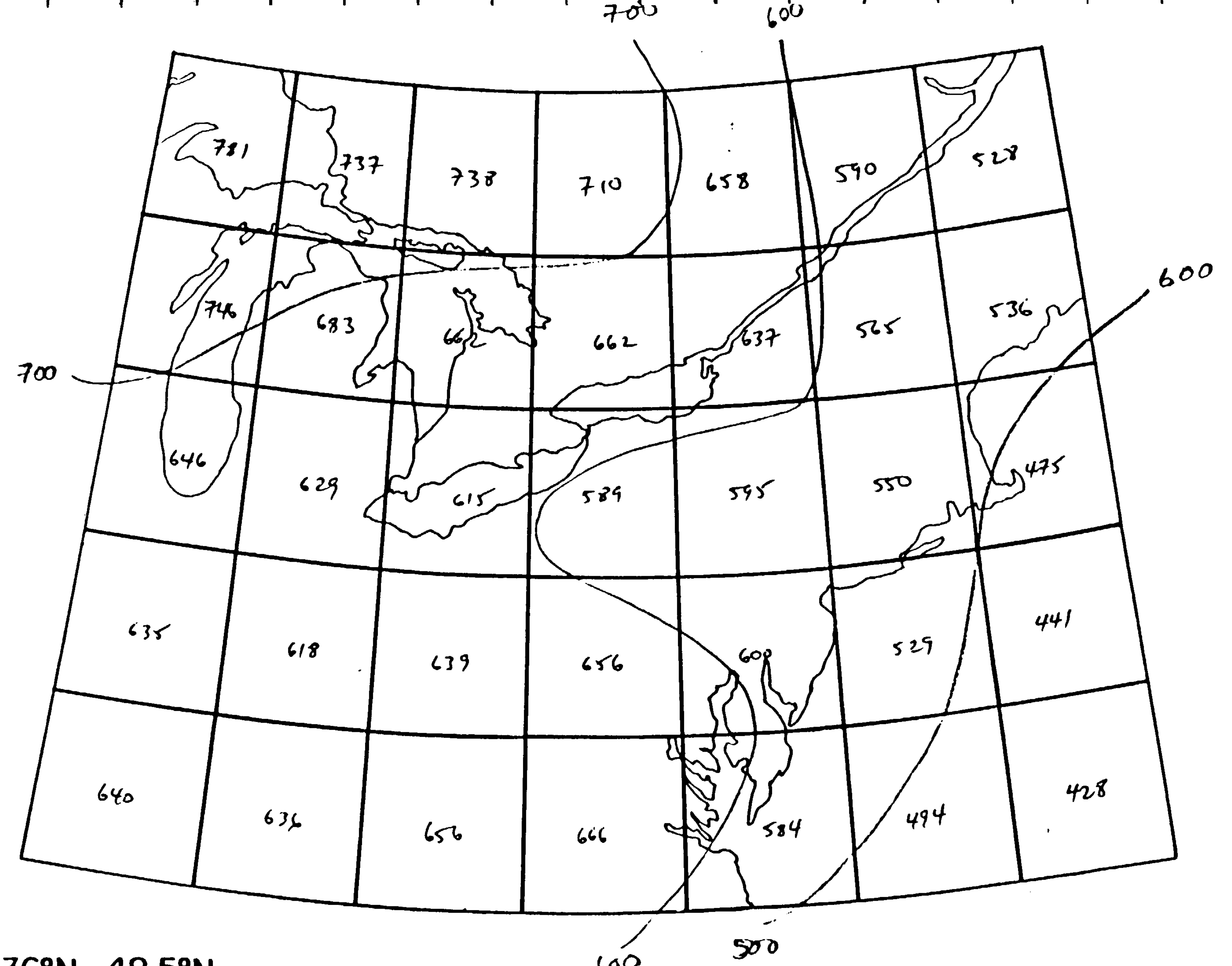
c) Cut-off moving across area

D. FEEDER BANDS

E. STRONG MID-LATITUDE TROF MOVING EAST

F. JET-STREAM SHEAR

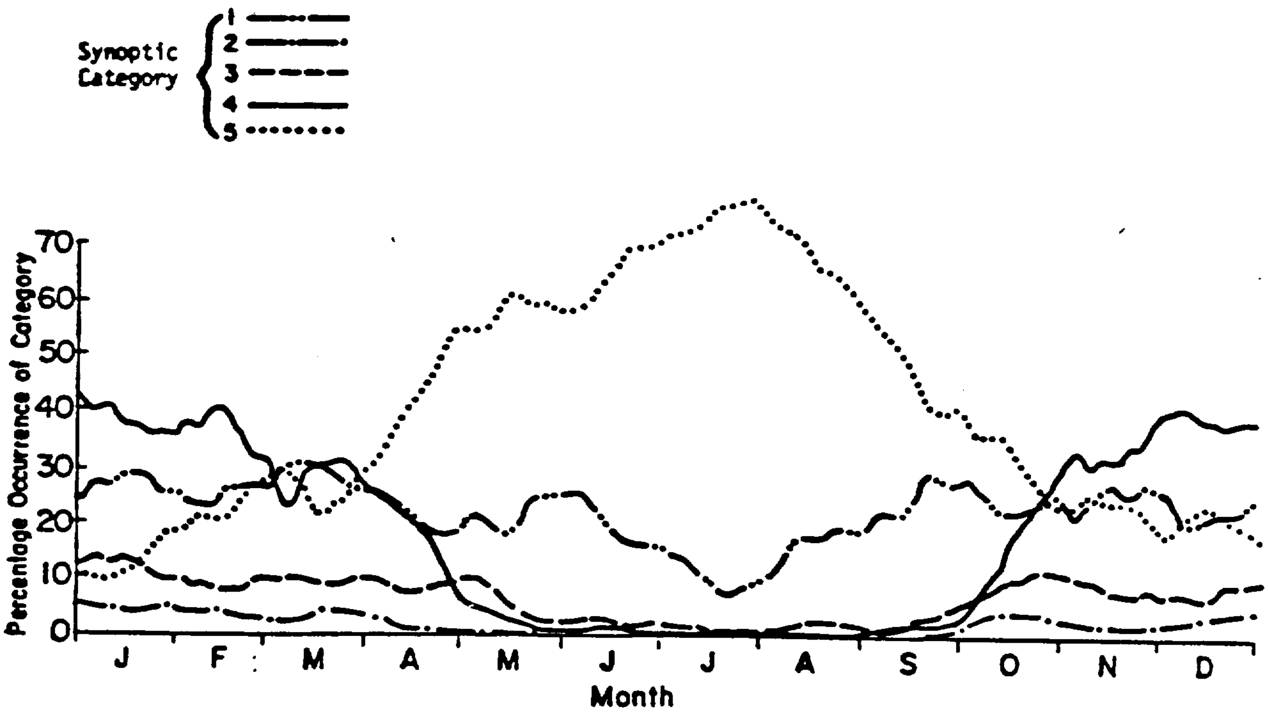
TROPICAL WAVE



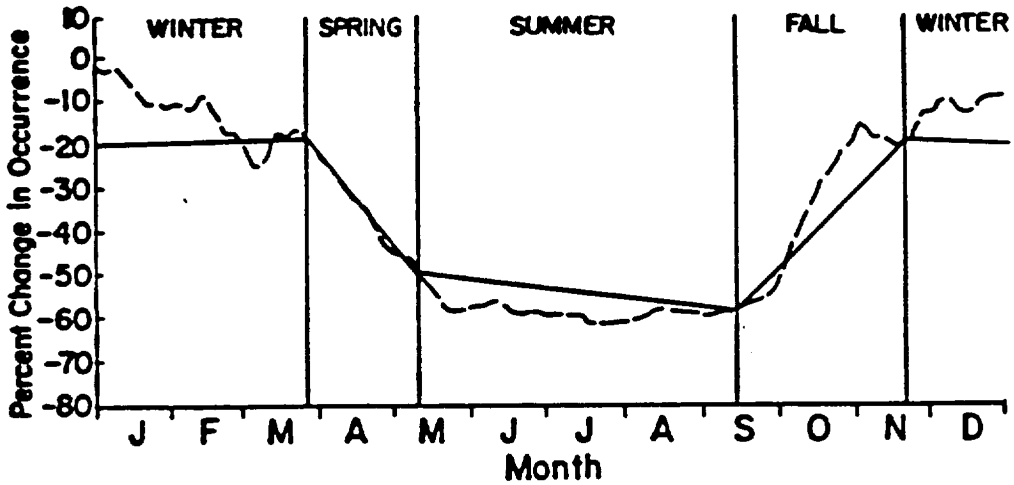
36°N-48.5°N
68°W-89°W

Joint number of occurrences of morning synoptic category versus afternoon mixing height class at Miami, Florida for the period 1971-1975 (1826 days). Numbers given in parentheses under each entry in the main body of the table are frequency of occurrence by column and frequency of occurrence by row, respectively, as percentages. Numbers given in parentheses under the column totals are frequencies of occurrence across the row as percentages; numbers given in parentheses beneath the row totals are frequencies of occurrence down the column as percentages. Note that the percentage frequency of occurrence values are rounded to whole percentages.

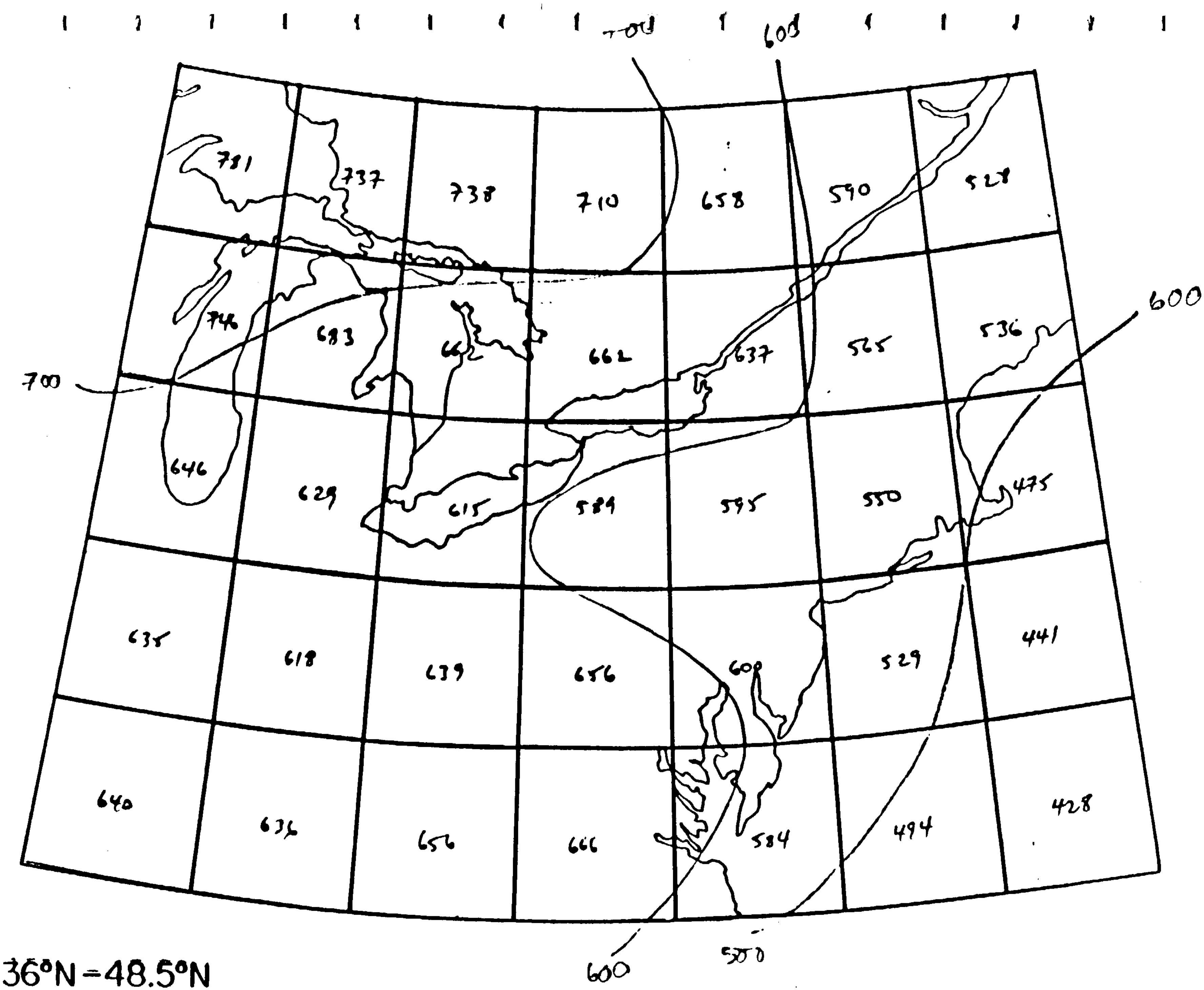
Synoptic Category	Afternoon Mixing Height Class (m)								Row Total
	0-200	201-400	401-700	701-1000	1001-1500	1501-2500	>2500	Missing	
1	8 (18/2)	9 (21/3)	26 (25/8)	52 (18/15)	156 (17/46)	75 (18/22)	1 (100/0)	10 (30/3)	337 (18)
2	0 (0/0)	0 (0/0)	3 (3/12)	8 (3/31)	12 (1/46)	3 (1/12)	0 (0/0)	0 (0/0)	26 (1)
3	2 (4/3)	6 (14/9)	12 (12/18)	15 (5/23)	16 (2/25)	8 (2/12)	0 (0/0)	6 (18/9)	65 (4)
4	6 (13/2)	7 (17/2)	20 (19/6)	51 (18/14)	156 (17/44)	105 (26/30)	0 (0/0)	7 (21/2)	352 (19)
5	19 (42/2)	14 (33/2)	36 (35/4)	147 (51/16)	500 (55/54)	206 (50/22)	0 (0/0)	8 (24/1)	930 (51)
U	10 (22/9)	6 (14/5)	6 (6/5)	17 (6/15)	63 (7/54)	12 (3/10)	0 (0/0)	2 (6/2)	116 (6)
Column Totals	45 (2)	42 (2)	103 (6)	290 (16)	903 (49)	409 (22)	1 (0)	33 (2)	1826 (100)



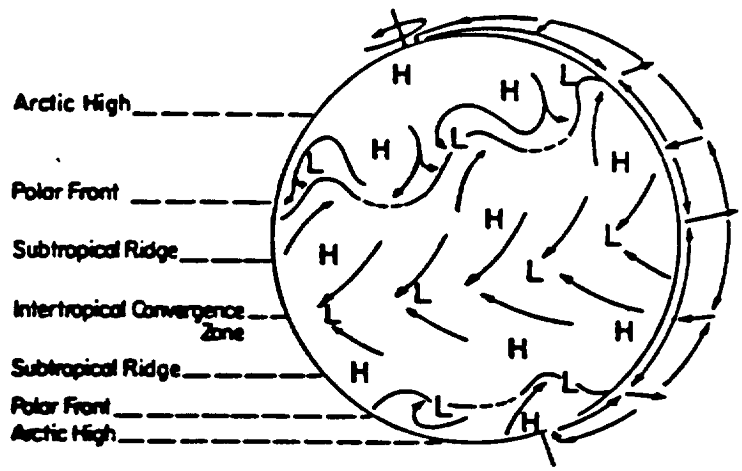
25-day weighted average frequency distributions of synoptic categories for Miami, Florida stations: Jan. 1, 1955 - Dec. 31, 1964, from Garstang et al. (1980), and Lindsey (1980).



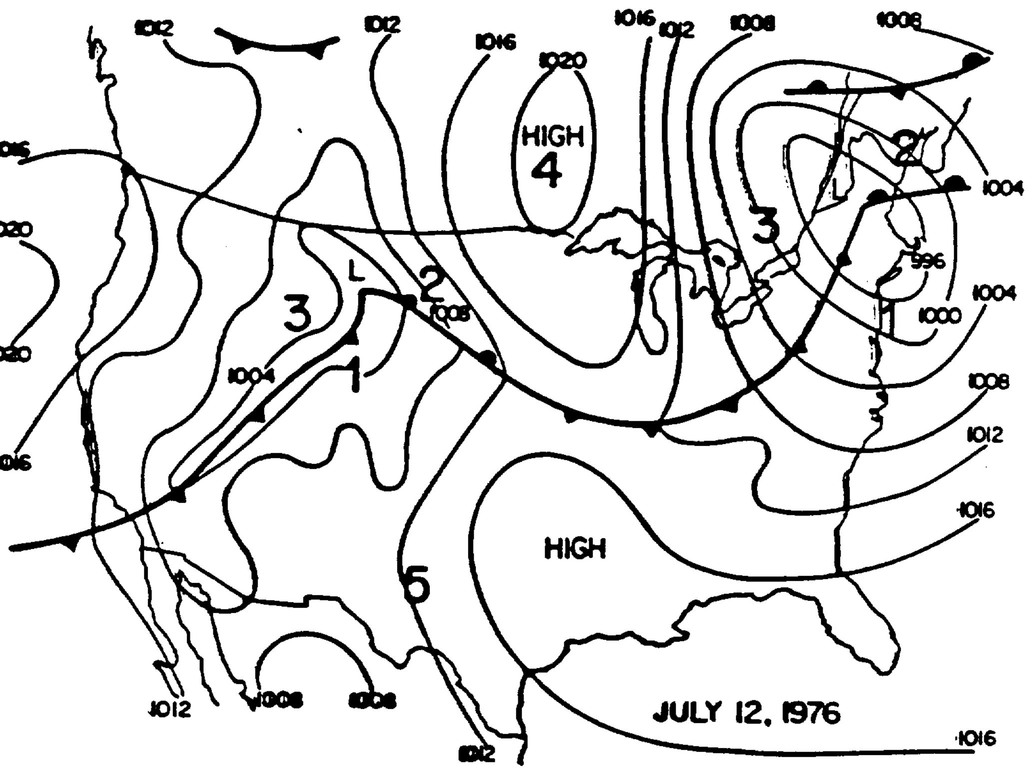
Changes in frequency of synoptic categories 2, 3 and 4 for Miami, FL - 1955-1964 using Figure 9.



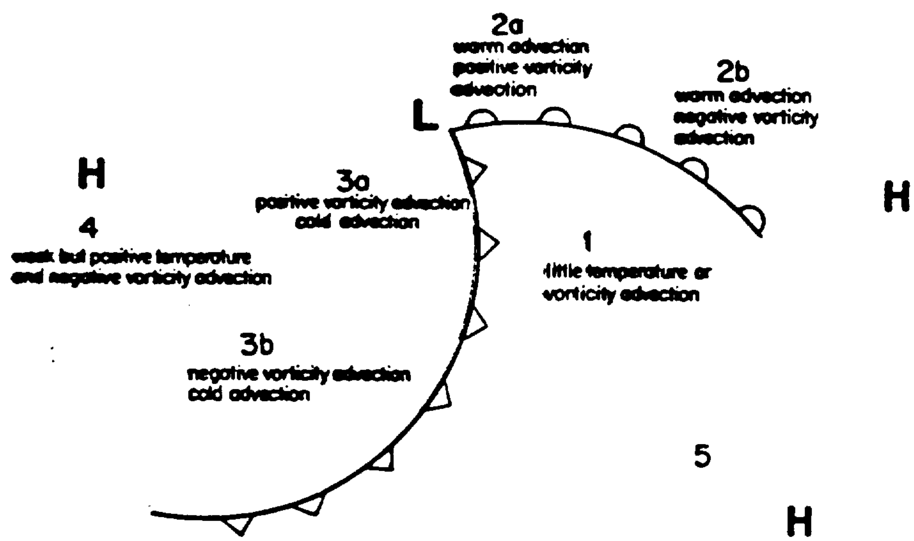
36°N–48.5°N
68°W–89°W



Schematic of the general circulation of the earth in the northern hemisphere winter. There is average subsidence in the subtropical ridge and arctic high, and average ascent in the intertropical convergence zone and polar front region. The polar front separates air from upper latitude origin from lower latitude origination.



Synoptic classification scheme illustrating typical (a) winter and (b) summer patterns.



Schematic as to how temperature and vorticity advection patterns could be used to refine synoptic classification scheme.

SCENARIO KNOWLEDGE ACQUISITION

TWFES FINAL PRESENTATION, PHASE TWO

GENERAL FORECASTING APPROACH

We are currently forecasting weather at KSC utilizing:

1. Experience-based reasoning (EBR)
2. AI techniques, tools, hardware, and software
3. Classical meteorological techniques (upper air analysis, etc.)
4. Mesoscale forecasting techniques
    a. Mesonet
    b. Field Mills
    c. LLP
    d. Radar
    e. Satellite
5. Numerical models
    a. Kaplan Mass Model *
    b. Pielke Sea Breeze Model
6. Statistical models
    a. Holle - Mesonet/LLP
    b. Neumann-Pfeffer *
7. Real model
    a. Sky visible to researcher (Presently the most obvious indicator of unforeseen change in earlier forecast)

* not working this year

TWFES FINAL PRESENTATION, PHASE TWO

EXPERIENCE-BASED REASONING APPROACH

1. Why experience-based reasoning approach here at KSC?

   a. Latitude

   b. Coastal

   c. Lack of data (upper air)

   d. Accuracy required by Shuttle Operations

   e. Deficiencies of

      1) Numerical models

      2) Statistics

      3) Mid latitude training

1. Advantages of experience-based system (EBS)

   a. A way to capture and store weather forecasting knowledge and experience gained over time at one geographic point.

   b. The EBS grows as more knowledge and experience is gained. Nothing is lost.

   c. Once a day is initialized into the system, a training and learning process is set into motion.

   d. Any deviations from the initialized weather scenario can be noted for future use.

   e. Using experienced-based weather forecasting logic and the concurrent observation of the sky is the most sensible method of mimicking the real model.

3. Why the passion to organize an EBS to aid management?

Simply because management needs a decision making tool which is best delivered by an experience-based forecasting system.

TWFES FINAL PRESENTATION, PHASE TWO

KSC THUNDERSTORM FORECASTING EBR APPROACH

Initial (month)

Quality assurance ==> Delta fields ==> Initialization ==>
of #'s U.A. U.A.

Persistence ==> Statistics and numerical models
(previous day) (scenarios)

Real Time (daily)

Scenario ==> Delta fields ==> TrigIN/TrigOUT
LLP
Field Mills
Mesonet
Radar
Spherics
Pyroheliometer

TWFES FINAL PRESENTATION, PHASE TWO

MANAGING THE USERS' EXPECTATIONS

1. Explain the ability of experience based reasoning to provide accurate weather forecasts with no margin for error.

2. Explain the preconceptions that have clouded the real meaning of the EBR approach:

a. EBR is not a panacea.

b. EBR is robust enough to handle the instrumental observation of reality.

c. EBS retains knowledge of one trying to mimic reality verbally in the real-time and past-time.

d. One of the most important aspects is the training capability of the EBS.

e. Numerical modeling and statistics based reasoning have a place in the forecast regimen but the meaning can only be interpreted based upon reality - "What does the sky look like?"

f. EBR groups all aspects of local weather forecasting into a sequential, logical and manageable real-time operational system.

TWFES FINAL PRESENTATION, PHASE TWO

KSC WEATHER RESEARCH LAB IN THE CIF

1. Direct visual observation of the sky

    a. 120 degrees thru 360 degrees from the lab

    b. Full 360 degrees from the roof

2. Instrumentation

    a. Symbolics LISP Machine (AI)

    b. PC AT clone

    c. DAB radar/looped

    d. LLP (cloud to ground lightning)

    e. DAB radar/LLP overlay

    f. Field Mills (electrostatic field charge)

    g. Mesonet (local and expanded)

    h. Satellite (26 different image types)

        1) Visual

        2) IR

        3) Water Vapor

        4) MIDDS

        5) MeteoSat (European satellite)

    i. Access to MIDDS terminal in the range control center for upper air data, satellite, etc.

    j. Roof camera with looping capabilities to be installed in October, 1987

    k. Pad 39B water tower camera

    l. Pyroheliometer (strip chart)

Lab is located at southwest corner of the CIF Building on the third floor in Room 334. The CIF is approximately 6 nm south of the SLF.

DESIDERATA FOR THE CIF

1. Weather Station Operations
   a. Analysis and forecasting techniques
   b. Analysis documentation (history)
   c. Data correlation (numbers vs. reality)
   d. Sky documentation and analysis correlations
   e. Mesonet/total column water/insolation correlations
   f. Instrumentation utilization techniques
   g. Satellite forecasting techniques
2. Instrumentation
   a. Doppler
   b. Profiler
   c. Mesonet
   d. Video (sky)
   e. LLP
   f. Field mills (lightning)
   g. PROFS terminal (mesoscale analysis techniques)
3. Projects
   a. Analysis and proper initialization of TWFES
   b. Numerical modeling
   c. Satellite research (thermal/water)
   d. Lightning research
   e. Mesonet
   f. Mesonet/water/wind correlations

IN-SITU RW/TRW

IN-SITU RW/TRW

OVERVIEW

- DETAILED ANALYSIS OF IN-SITU DEVELOPMENT DURING SUMMER 87

- PRELIMINARY LOGIC DEVELOPED FOR COMPLETE SET OF IN-SITU SCENARIOS

- RESULTS VERY ENCOURAGING BUT LIMITED BY DATA AVAILABILITY

- DEVELOPED LOGIC INCLUDES:

    - -- INITIALIZATION (TRIGGER-IN)

    - -- ABANDONMENT (TRIGGER-OUT)

    - -- REAL TIME (EVENT SEQUENCE)

IN-SITU RW/TRW

LOGIC DESCRIPTION

- MEAN LOW-LEVEL WIND MAIN DETERMINANT OF BEHAVIOR TYPE

- TIME WINDOWS (LOCAL) BY WIND DIRECTION:

  -- EAST: 9:30-13:00

  -- SOUTH/VARIABLE: 10:15-13:30

  -- WEST: 11:00- 14:30

    70% 11:00-13:00

    50% 12:30-13:00

- INITIALIZATION LOGIC VERIFICATION 35%-75%, AVERAGING 50%

- REAL-TIME LOGIC VERIFICATION 50%, WOULD EVENTUALLY APPROACH 100%

IN-SITU RW/TRW

ANALYSIS TECHNIQUES

- UPSTREAM UPPER-AIR DATA AND WATER VAPOR IMAGERY PROVIDE INFORMATION ON ADVECTION OF UPSTREAM CONDITIONS BETWEEN SOUNDINGS

- VISUAL INSPECTION OF IN-SITU CELLS PROVIDES INFORMATION ON GROWTH AND DECAY RATES, AS WELL AS DIRECT CONFIRMATION OF UPPER-AIR DATA

- VISIBLE SATELLITE IMAGERY PROVIDES FAVORED LOCATION OF CB DEVELOPMENT 1-3 HOURS PRIOR

- MESONET WINDS SHOW LOCATION AND SHAPE OF SEA BREEZE BOUNDARY, WHICH IS A GOOD REAL-TIME INDICATOR OF RAPID CB GROWTH

- RADAR CONFIRMS ONSET OF IN-CLOUD PRECIPITATION

- FIELD MILLS PROVIDE IMMINENT WARNING OF LIGHTNING DISCHARGE AND LIKELIHOOD OF CONTINUED CELL DEVELOPMENT

IN-SITU RW/TRW

REAL-TIME ROUTINE

- IF STRONG LIKELIHOOD EXISTS FOR IN-SITU:

  -- ANALYZE VIS SAT FOR FAVORED LOCATION

  -- VISUALLY INSPECT INITIAL TCu FOR UPDRAFT STRENGTH, MOISTURE CONTENT, VERTICAL SHEAR

  -- MONITOR MESONET FOR INDICATORS OF RAPID GROWTH

  -- ANALYZE VIS SAT TO IDENTIFY BRIGHT, DENSE, CLUMPS

  -- VISUALLY INSPECT LARGEST TCu FOR SIGNS OF CONTINUED GROWTH

  -- MONITOR RADAR FOR FIRST LEVEL 1 DVIP ECHO

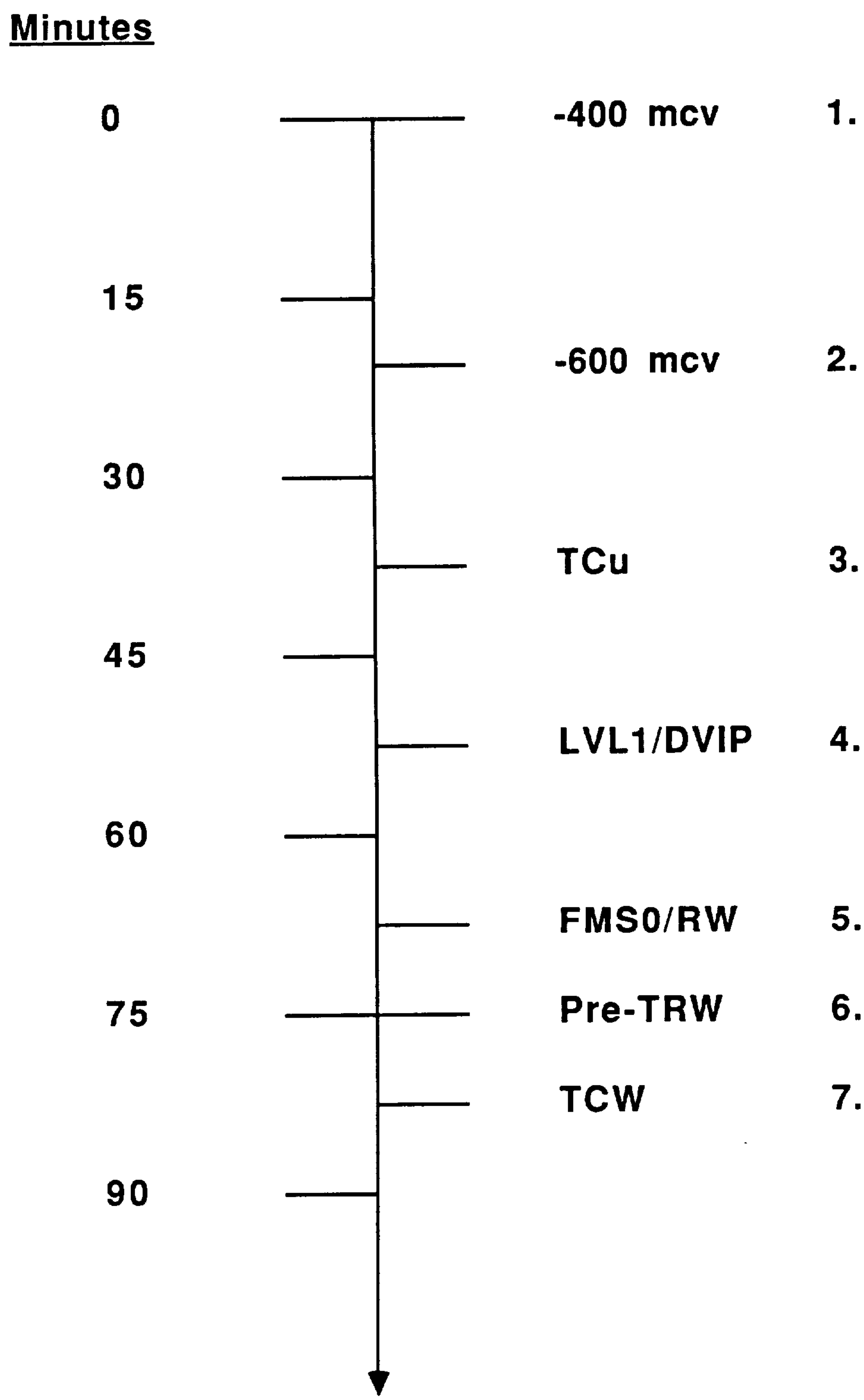
  -- MONITOR FIELD MILLS FOR DEVIATION FROM "FAIR WEATHER"

  -- VISUALLY INSPECT FOR MATURE CBs

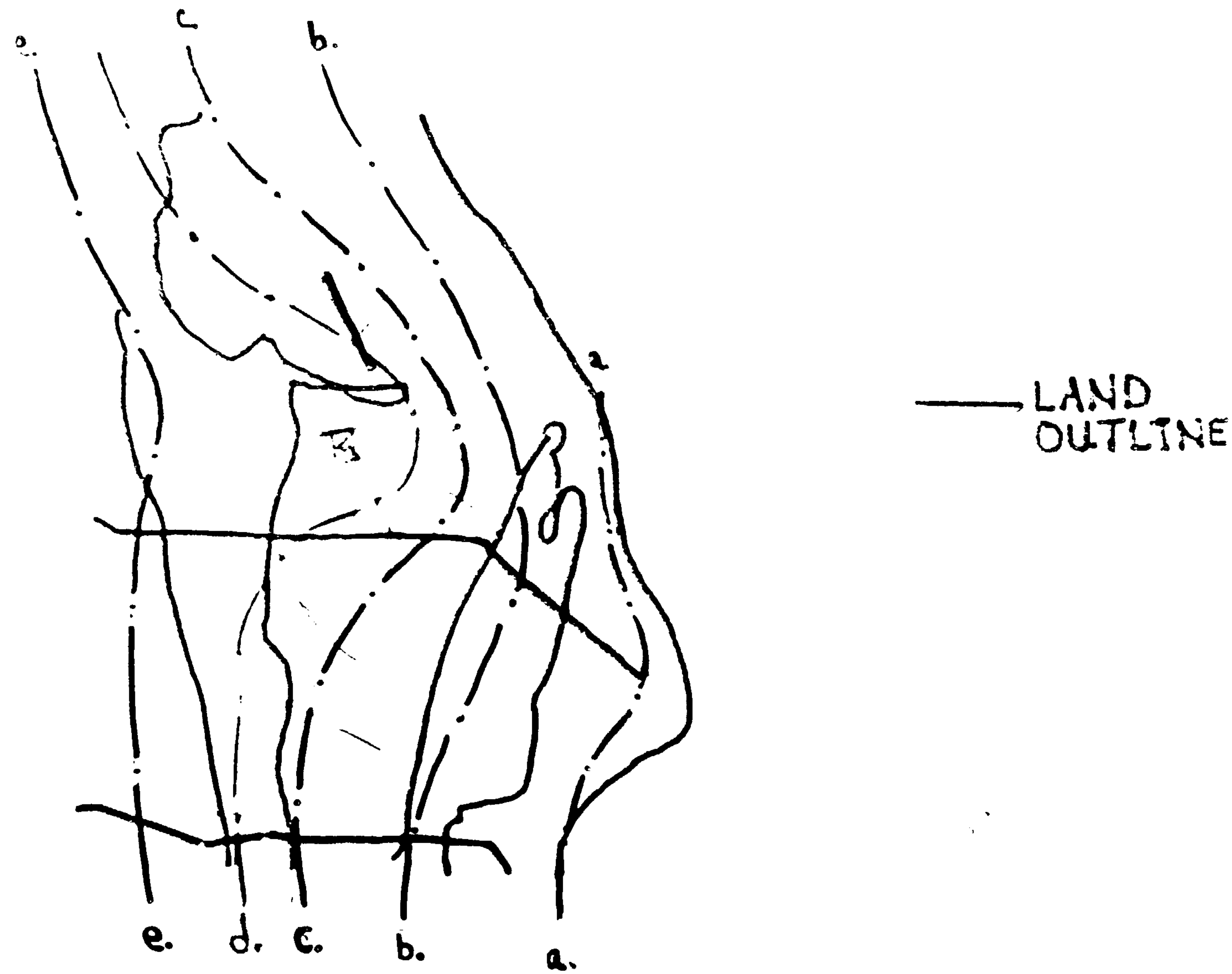
- Expect imminent lightning discharge

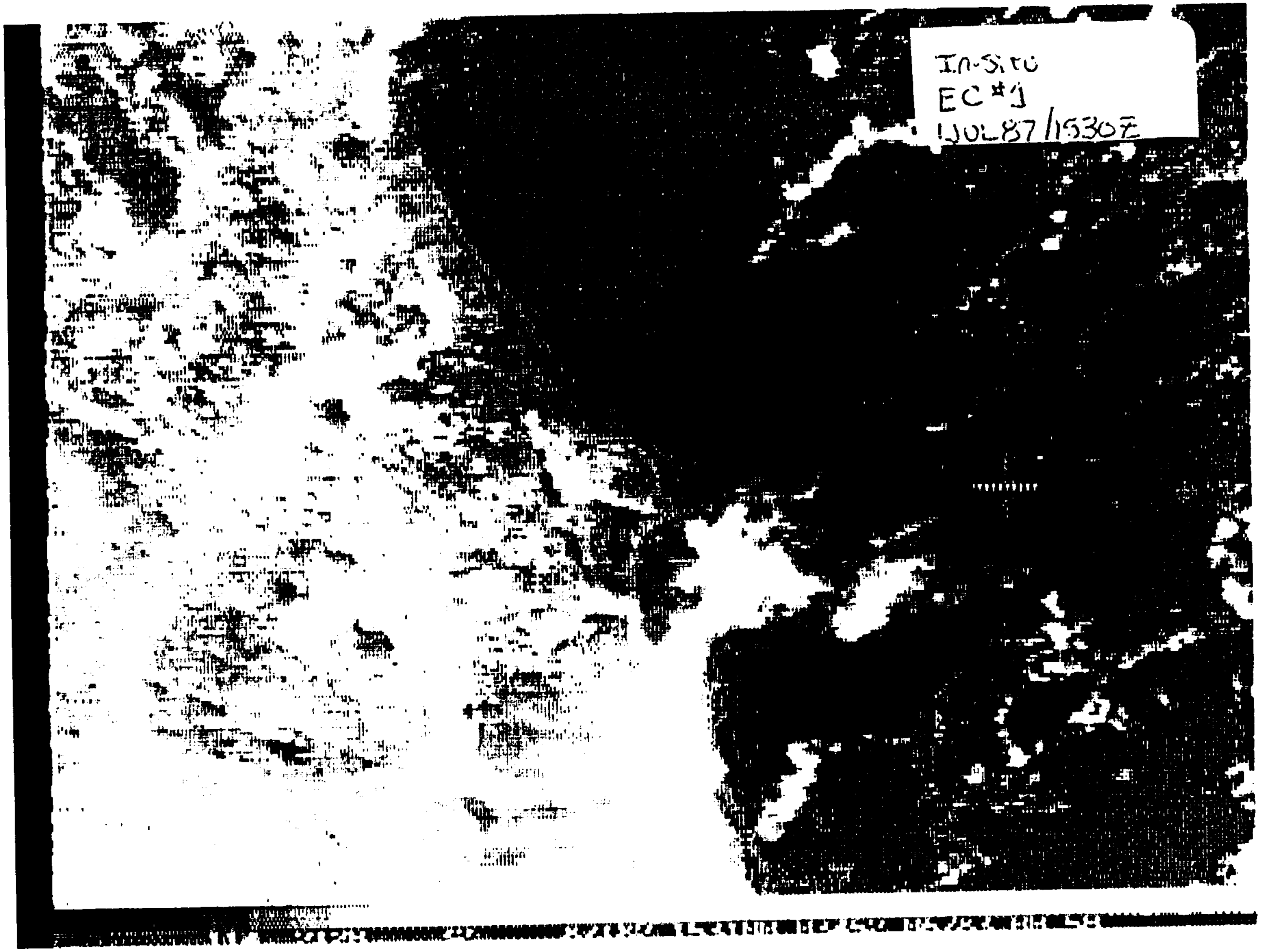
<u>IN-SITU RW/TRW</u>

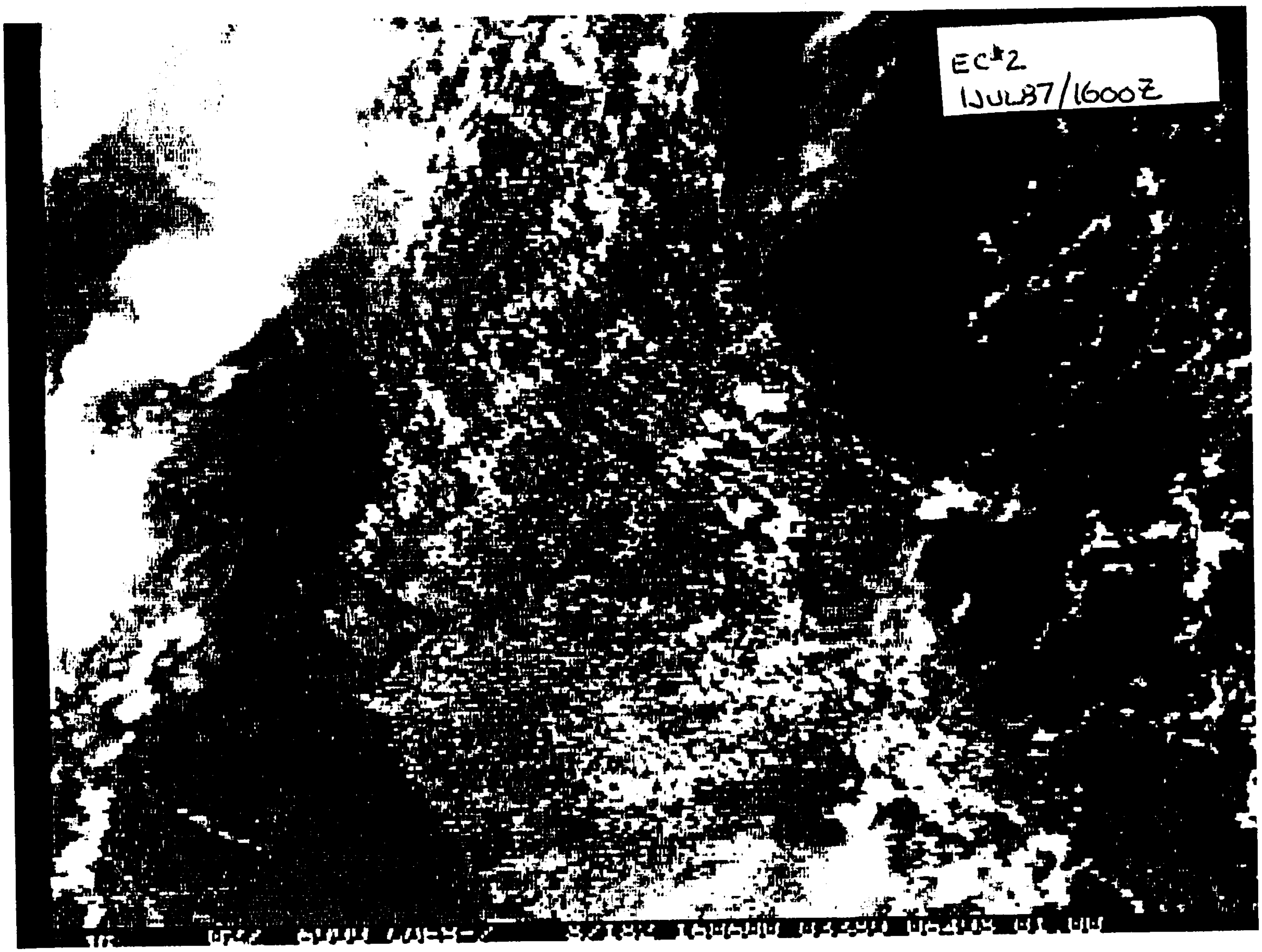
IN SITU EVENT TIME-LINE ; GRAPH 2

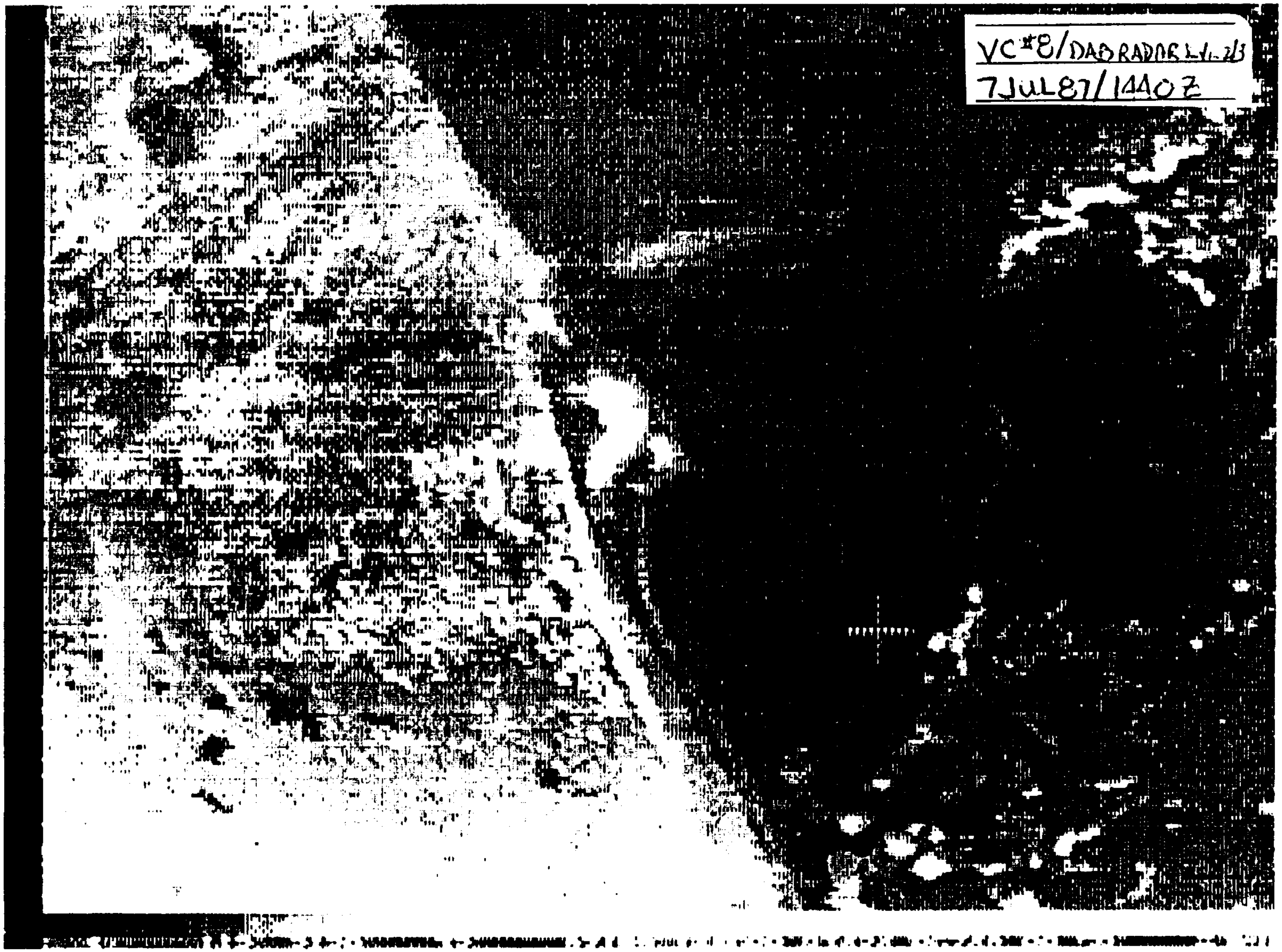


Appendix 1: Progression of SEA Breeze Over KSC/CCAFS

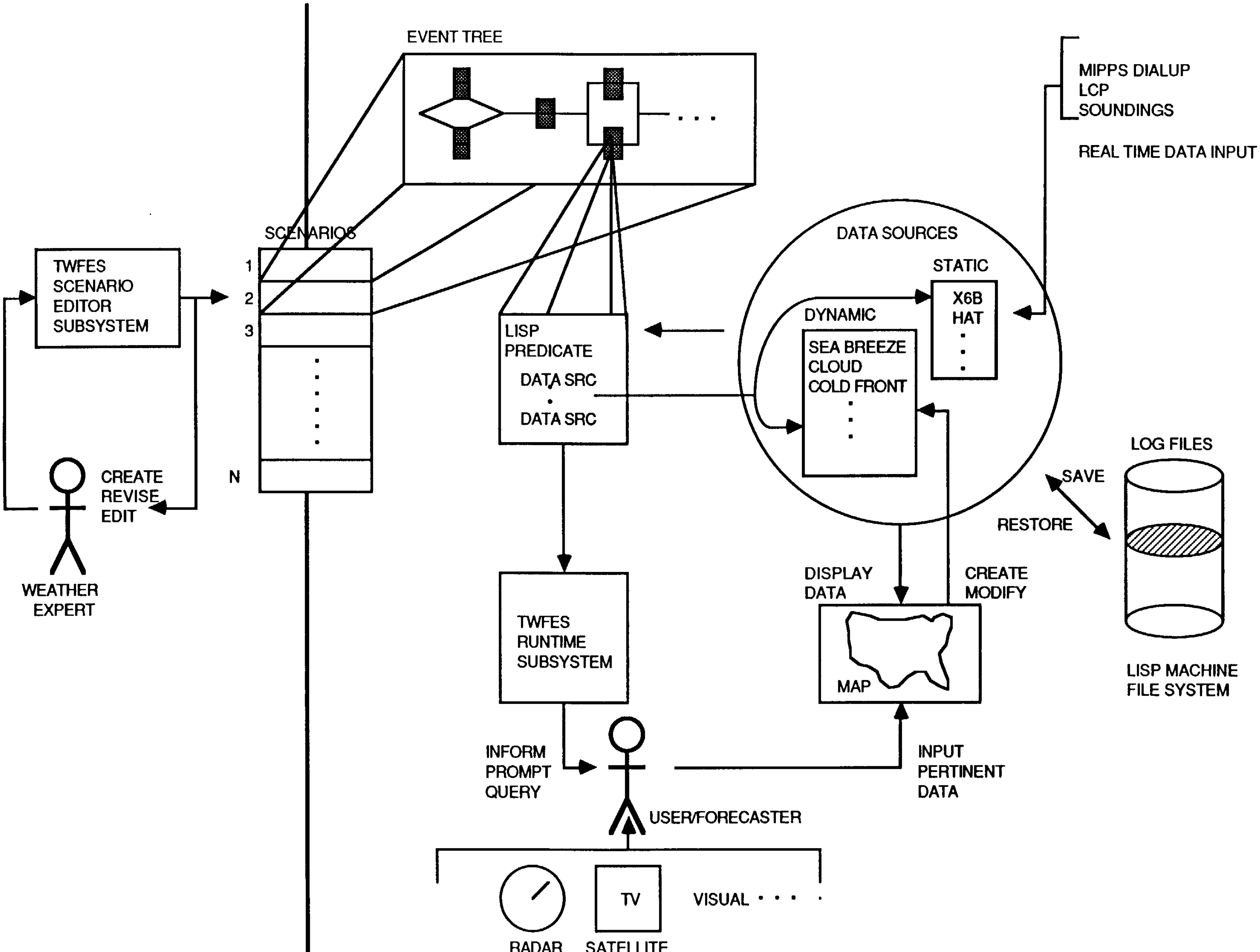



In-Situ
EC #1
1JUL87/1530Z

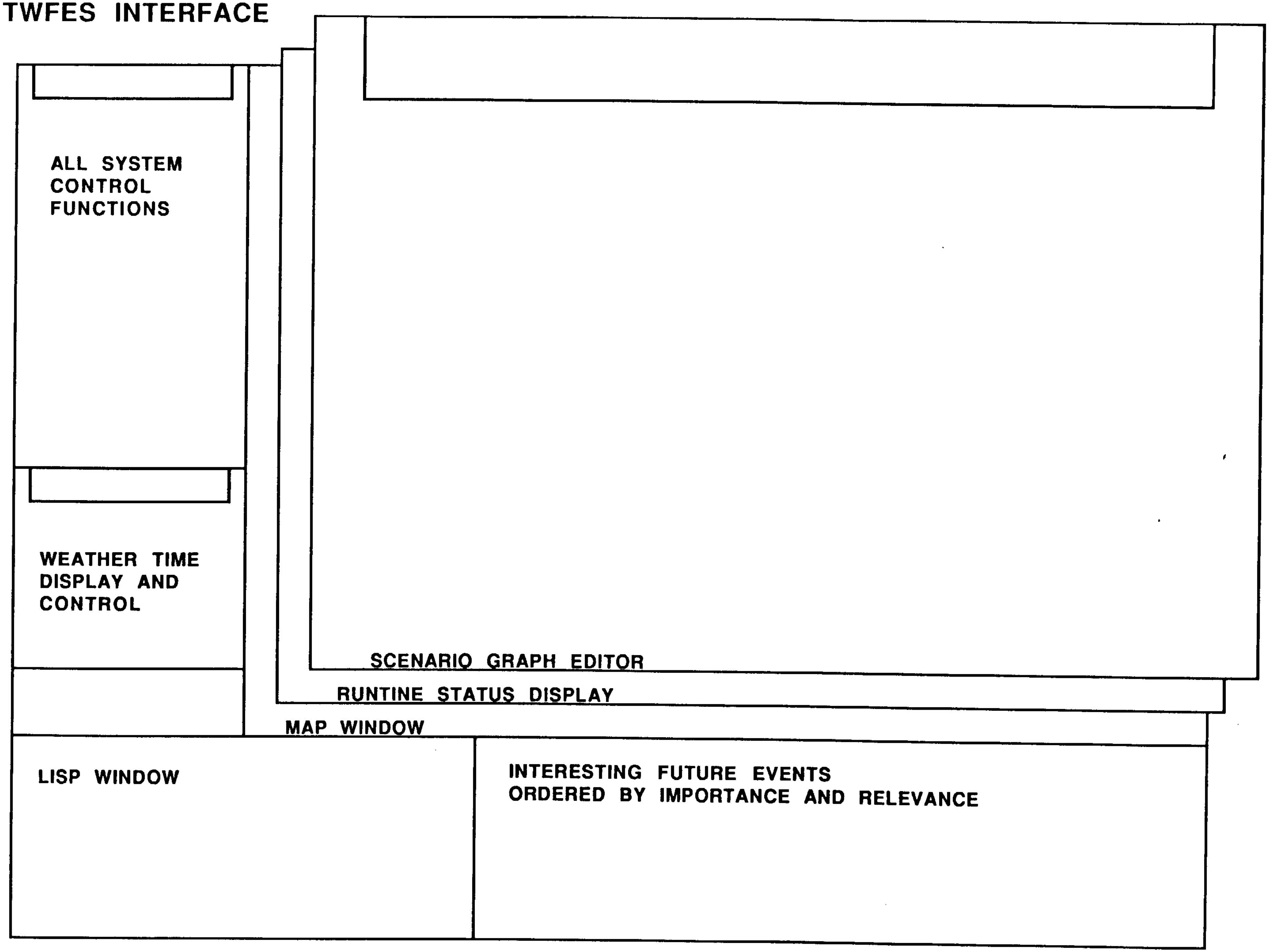

EC*2
1JUL87/1600Z

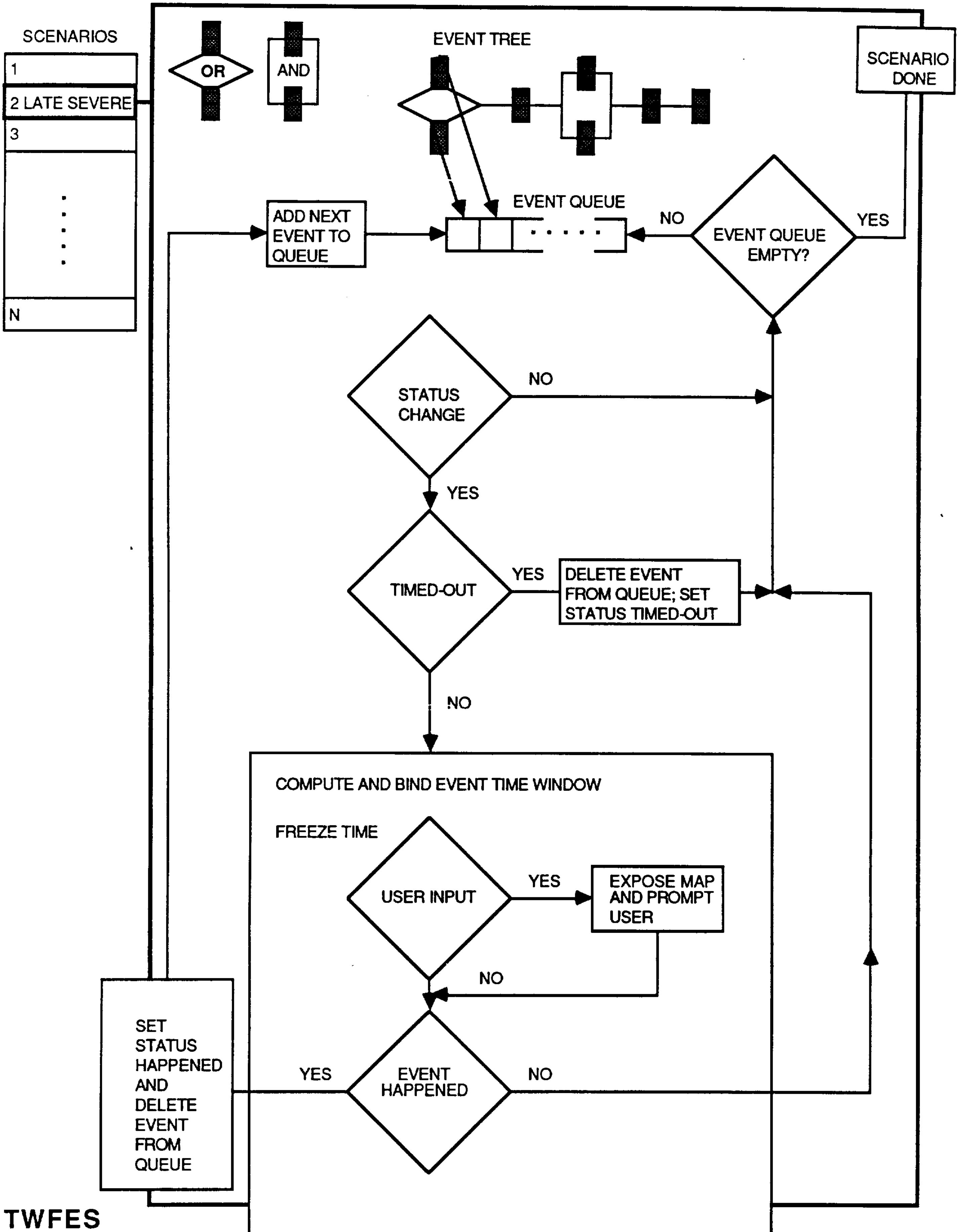

VC#8/DAB RADAR LVL 2/3
7JUL87/1440Z

TWFES ARCHITECTURE


EVENT TREE
MIPPS DIALUP
LCP
SOUNDINGS
REAL TIME DATA INPUT
SCENARIOS
1
2
3
N
TWFES
SCENARIO
EDITOR
SUBSYSTEM
CREATE
REVISE
EDIT
WEATHER
EXPERT
LISP
PREDICATE
DATA SRC
DATA SRC
DATA SOURCES
STATIC
X6B
HAT
DYNAMIC
SEA BREEZE
CLOUD
COLD FRONT
LOG FILES
SAVE
RESTORE
LISP MACHINE
FILE SYSTEM
DISPLAY
DATA
CREATE
MODIFY
MAP
TWFES
RUNTIME
SUBSYSTEM
INFORM
PROMPT
QUERY
INPUT
PERTINENT
DATA
USER/FORECASTER
RADAR
TV
SATELLITE
VISUAL

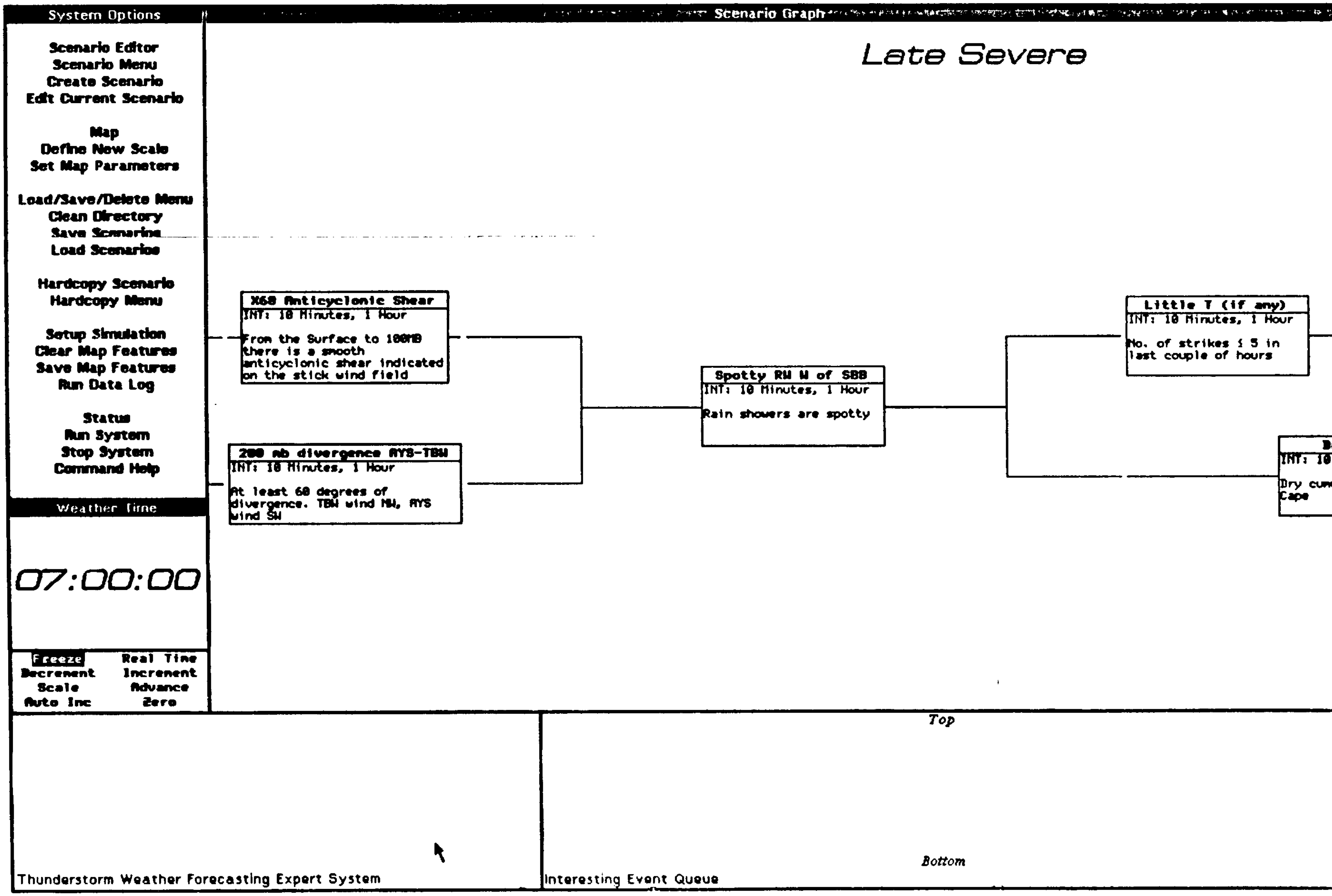
TWFES INTERFACE

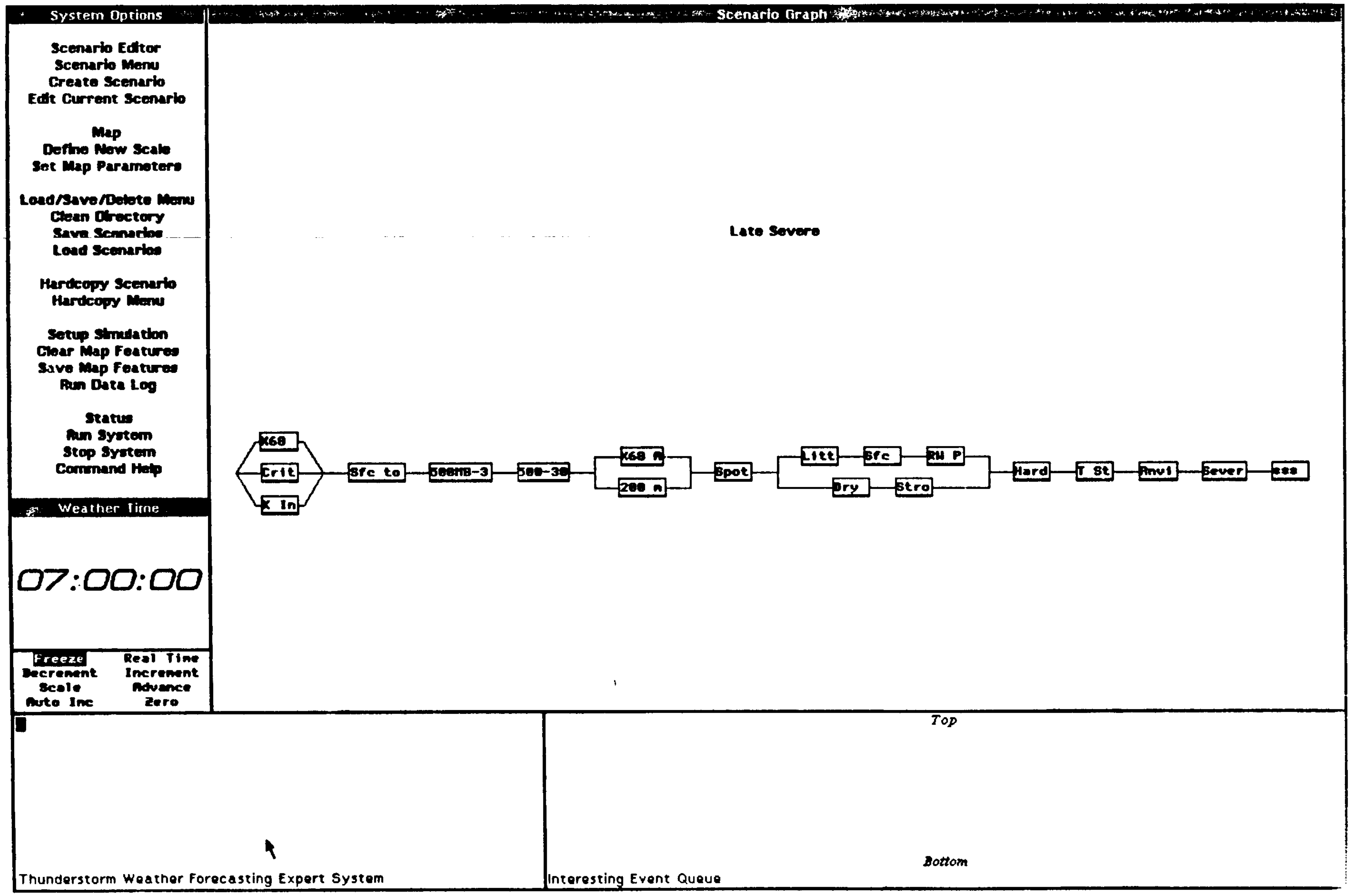




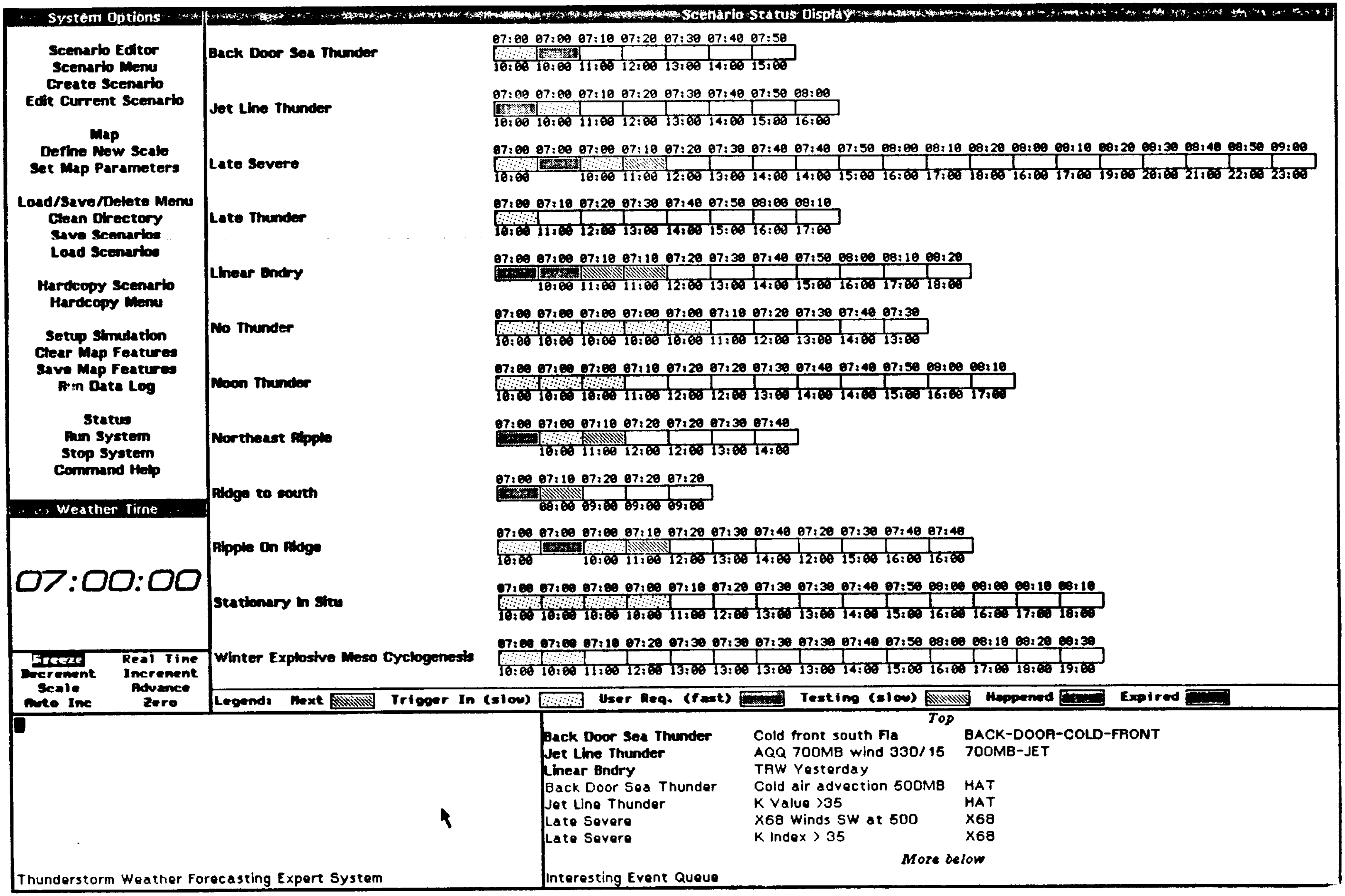
TWFES RUNTIME

SCENARIO GRAPH EDITOR

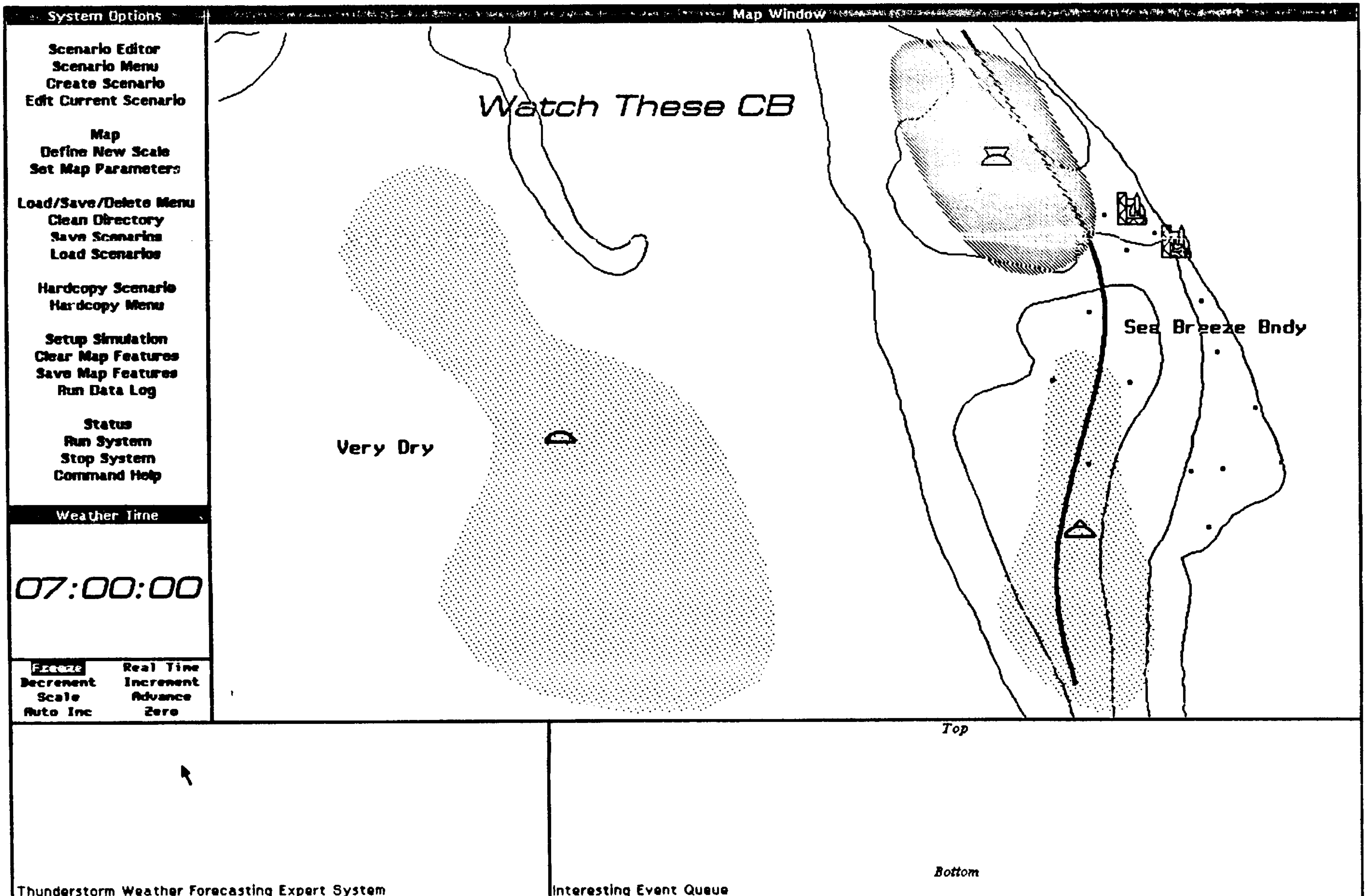

System Options
Scenario Graph
Late Severe
Scenario Editor
Scenario Menu
Create Scenario
Edit Current Scenario
Map
Define New Scale
Set Map Parameters
Load/Save/Delete Menu
Clean Directory
Save Scenarios
Load Scenarios
Hardcopy Scenario
Hardcopy Menu
Setup Simulation
Clear Map Features
Save Map Features
Run Data Log
Status
Run System
Stop System
Command Help
X68 Anticyclonic Shear
INT: 10 Minutes, 1 Hour
From the Surface to 100MB there is a smooth anticyclonic shear indicated on the stick wind field
200 mb divergence AYS-TBW
INT: 10 Minutes, 1 Hour
At least 60 degrees of divergence. TBW wind NW, AYS wind SW
Spotty RW W of SBB
INT: 10 Minutes, 1 Hour
Rain showers are spotty
Little T (if any)
INT: 10 Minutes, 1 Hour
No. of strikes ≤ 5 in last couple of hours
Weather Time
07:00:00
Freeze
Real Time
Decrement
Increment
Scale
Advance
Auto Inc
Zero
Top
Bottom
Thunderstorm Weather Forecasting Expert System
Interesting Event Queue


System Options
Scenario Graph
Scenario Editor
Scenario Menu
Create Scenario
Edit Current Scenario
Map
Define New Scale
Set Map Parameters
Load/Save/Delete Menu
Clean Directory
Save Scenarios
Load Scenarios
Hardcopy Scenario
Hardcopy Menu
Setup Simulation
Clear Map Features
Save Map Features
Run Data Log
Status
Run System
Stop System
Command Help
Late Severe
X60
Crit
X In
Sfc to
500MB-3
500-30
X60 A
200 m
Spot
Litt
Sfc
RW P
Dry
Stro
Hard
T St
Anvi
Sever
Weather Time
07:00:00
Freeze
Real Time
Decrement
Increment
Scale
Advance
Auto Inc
Zero
Top
Bottom
Thunderstorm Weather Forecasting Expert System
Interesting Event Queue

RUN TIME STATUS DISPLAY


System Options
Scenario Editor
Scenario Menu
Create Scenario
Edit Current Scenario
Map
Define New Scale
Set Map Parameters
Load/Save/Delete Menu
Clean Directory
Save Scenarios
Load Scenarios
Hardcopy Scenario
Hardcopy Menu
Setup Simulation
Clear Map Features
Save Map Features
Run Data Log
Status
Run System
Stop System
Command Help
Weather Time
07:00:00
Freeze
Real Time
Decrement
Increment
Scale
Advance
Auto Inc
Zero
Scenario Status Display
Back Door Sea Thunder
07:00 07:00 07:10 07:20 07:30 07:40 07:50
10:00 10:00 11:00 12:00 13:00 14:00 15:00
Jet Line Thunder
07:00 07:00 07:10 07:20 07:30 07:40 07:50 08:00
10:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00
Late Severe
07:00 07:00 07:00 07:10 07:20 07:30 07:40 07:40 07:50 08:00 08:10 08:20 08:00 08:10 08:20 08:30 08:40 08:50 09:00
10:00 10:00 11:00 12:00 13:00 14:00 14:00 15:00 16:00 17:00 18:00 16:00 17:00 19:00 20:00 21:00 22:00 23:00
Late Thunder
07:00 07:10 07:20 07:30 07:40 07:50 08:00 08:10
10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00
Linear Bndry
07:00 07:00 07:10 07:10 07:20 07:30 07:40 07:50 08:00 08:10 08:20
10:00 11:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00
No Thunder
07:00 07:00 07:00 07:00 07:00 07:10 07:20 07:30 07:40 07:30
10:00 10:00 10:00 10:00 10:00 11:00 12:00 13:00 14:00 13:00
Noon Thunder
07:00 07:00 07:00 07:10 07:20 07:20 07:30 07:40 07:40 07:50 08:00 08:10
10:00 10:00 10:00 11:00 12:00 12:00 13:00 14:00 14:00 15:00 16:00 17:00
Northeast Ripple
07:00 07:00 07:10 07:20 07:20 07:30 07:40
10:00 11:00 12:00 12:00 13:00 14:00
Ridge to south
07:00 07:10 07:20 07:20 07:20
08:00 09:00 09:00 09:00
Ripple On Ridge
07:00 07:00 07:00 07:10 07:20 07:30 07:40 07:20 07:30 07:40 07:40
10:00 10:00 11:00 12:00 13:00 14:00 12:00 15:00 16:00 16:00
Stationary In Situ
07:00 07:00 07:00 07:00 07:10 07:20 07:30 07:30 07:40 07:50 08:00 08:00 08:10 08:10
10:00 10:00 10:00 10:00 11:00 12:00 13:00 13:00 14:00 15:00 16:00 16:00 17:00 18:00
Winter Explosive Meso Cyclogenesis
07:00 07:00 07:10 07:20 07:30 07:30 07:30 07:30 07:40 07:50 08:00 08:10 08:20 08:30
10:00 10:00 11:00 12:00 13:00 13:00 13:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Legend: Next Trigger In (slow) User Req. (fast) Testing (slow) Happened Expired
Thunderstorm Weather Forecasting Expert System
Top
Back Door Sea Thunder Cold front south Fla BACK-DOOR-COLD-FRONT
Jet Line Thunder AQQ 700MB wind 330/15 700MB-JET
Linear Bndry TRW Yesterday
Back Door Sea Thunder Cold air advection 500MB HAT
Jet Line Thunder K Value >35 HAT
Late Severe X68 Winds SW at 500 X68
Late Severe K Index > 35 X68
More below
Interesting Event Queue

MAP WINDOW


System Options
Scenario Editor
Scenario Menu
Create Scenario
Edit Current Scenario
Map
Define New Scale
Set Map Parameters
Load/Save/Delete Menu
Clean Directory
Save Scenarios
Load Scenarios
Hardcopy Scenario
Hardcopy Menu
Setup Simulation
Clear Map Features
Save Map Features
Run Data Log
Status
Run System
Stop System
Command Help
Weather Time
07:00:00
Freeze
Real Time
Decrement
Increment
Scale
Advance
Auto Inc
Zero
Map Window
Watch These CB
Very Dry
Sea Breeze Bndy
Top
Bottom
Thunderstorm Weather Forecasting Expert System
Interesting Event Queue

SUMMARY AND FUTURE DIRECTIONS

SUMMARY ISSUES

METEOROLOGICAL JUSTIFICATION

FOR THE TWFES ARCHITECTURE

- BASIC BEHAVIOR TYPES CAN BE IDENTIFIED

- SEA BREEZE CONVECTION RELATIVELY SIMPLE

- SHORT-TERM PHENOMENA CANNOT BE MODELED:

  MUST RESORT TO HUMAN INTERPRETATION

- REAL-TIME SIGNATURES READILY APPARENT BUT IDENTIFICATION REQUIRES INTEGRATION OF MULTIPLE DATA SOURCES:

  -- FORCING OF IN-SITU TCu

  -- CAPE "GEOCONVERGENCE"

  -- "JET LINE" STORMS

  -- LOW-LEVEL MORNING INVERSION

SUMMARY ISSUES

METEOROLOGICAL JUSTIFICATION

FOR THE TWFES ARCHITECTURE

(CONTINUED)

- SIGNATURES ARE TIME-DEPENDENT: STATIC ANALYSIS IS NOT SUFFICIENT

- THERFORE, REQUIRES AN ARCHITECTURE WHICH:

  -- CLASSIFIES DAY USING LARGE-SCALE PARAMETERS

  -- MONITORS REAL-TIME PHENOMENA AS A PROCESS

- OTHERS ARE PURSUING SIMILAR IDEAS:

  -- PIELKE (COLORADO STATE UNIVERSITY)

  -- BROWN (UK METEOROLOGICAL OFFICE)

  -- FLUID ANALOGICAL REASONING GROUP (ANN ARBOR)

  -- FIELD (NEW MEXICO STATE UNIVERSITY)

SUMMARY ISSUES

TWFES SOFTWARE

- FROM AN ENGINEERING PERSPECTIVE, TWFES IS A GOOD APPLICATION OF AI TECHNOLOGY:

  -- MIXTURE OF QUALITATIVE AND QUANTITATIVE JUDGEMENT

  -- EXPERIENCE-BASED KNOWLEDGE

  -- HIGH-QUALITY DATA AVAILABLE

  -- MINIMAL "COMPUTER PHOBIA" IN USER POPULATION

  -- ARTICULATE, VERBAL EXPERTS AVAILABLE

- THE CURRENT TWFES RUNS FASTER THAN REQUIRED FOR REAL TIME OPERATION

FUTURE DIRECTIONS: DESIGN

- DYNAMIC MODIFICATION OF PRE-COMPILED SCENARIOS (OTHER THAN TIMING)

  I.E., ACCELERATORS, DELAYERS, ENHANCERS, DETRACTORS

- DYNAMIC CREATION OF "SCENARIOS"

  -- DEVIATION FORM YESTERDAY (TO CREATE "SCENARIO" SLIGHTLY DIFFERENT FROM YESTERDAY

  -- FIRST PRINCIPLES (TO CREATE TIME DEPENDENT CAUSAL CHAINS)

- ADDITION OF EXISTING PATTERN RECOGNITION ALGORITHMS TO EVENT PREDICATES

  -- SIGNAL PROCESSING

  -- IMAGE ANALYSIS

- INTEGRATION WITH EXISITING MESOSCALE MODELS (USE MODEL AS DATA SOURCE)

FUTURE DIRECTIONS: SOFTWARE

- INITIALIZATION ANALYSIS (1200Z SOUNDINGS)

- ADDITIONAL INPUT DATA:
  - -- FIELD MILLS
  - -- STATION B OBSERVATIONS

- ADDITIONAL DISPLAY CAPABILITY:
  - -- IMAGERY
  - -- FIELD MILLS
  - -- OTHER LOCAL DATA

- CUSTOM LANGUAGE FOR EVENT PREDICATES

FUTURE DIRECTIONS: KNOWLEDGE ENGINEERING

METEOROLOGICAL

- ANALYZE DAILY LOGS FROM SUMMER 87
- GENERALIZE AND EXPAND CURRENT SCENARIOS
- BEGIN WORK ON LOGIC TO CAPTURE CONVECTIVE PHYSICS (FOR AUTO-CREATION OF SCENARIOS)

OPERATIONAL

- MODELING OF THE CCFF TASK ENVIRONMENT
- IDENTIFICATION OF APPROPRIATE OPERATIONAL SYSTEM ROLE
- SPECIFICATION OF DETAILED USER INTERFACE
- INSTALLATION, TESTING AND VERIFICATION AT CCFF

DISCUSSION AND CRITIQUE

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS EASTERN SPACE AND MISSILE CENTER (AFSC)
PATRICK AIR FORCE BASE, FLORIDA 32925

REPLY TO ATTN OF: WE (494-5915)

20 Oct 87

SUBJECT: Thunderstorm Expert System Effort

TO: KSC/DL-DSD-22 (Art Beller)

1. As a result of the 30 Sep 87 Program Review we evaluated the potential of the thunderstorm expert system for use in the CCFF. We think the system shows potential for applications in four areas: (a) to codify and validate existing knowledge about various thunderstorm scenarios, (b) as an operational forecast tool, (c) as a training tool for thunderstorm forecasting, and (d) as an alarm to notify a forecaster when a set of criteria is exceeded. Although the system shows potential, it is still a laboratory system, and should be evaluated in an operational setting—the CCFF.

2. Before the system can be placed in the CCFF, it must undergo further development and we must evaluate and validate existing scenarios. Specifically the system must be able to (a)select the appropriate scenarios rather than require the forecaster to choose a scenario, (b) initialize or reinitialize at any time, (c) record data for use in a training environment, (d) automatically access the MIDDS data base, (e) monitor data and alert the forecaster when selected values are exceeded. In addition a user's manual and training manual must be developed for use in the CCFF.

3. The first priority for my limited resources must be operational requirements rather than development. Thus, before the system is placed in the CCFF for evaluation, clearly defined objectives must be documented along with a plan of action. The plan must include range certification and software configuration control.

John T. Madura

JOHN T. MADURA, Colonel, USAF
Staff Meteorologist

cc: 2WS/DR

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories
325 Broadway
Boulder, Colorado 80303

October 13, 1987 R/E2

Arthur Beller
Kennedy Space Center
Mail Code DL-DSD-22
Kennedy Sp Ctr FL 32899

Dear Art:

It was again a pleasure to attend a TWFES review. Listed below are some general comments on the program:

1. I was most interested to hear that you have chosen to leave ART and go entirely to lisp, for reasons of speed and maintainability. We haven't used tools here, believing that their limitations would get in our way in the long run. Your experience suggests that perhaps we were right. It was not clear to me, however, where speed is important in an operational sense. I still wonder whether it wouldn't have been more valuable to stay with the slower system and invest time and money looking more directly at operational needs and "tuning" the knowledge base.

2. I believe more than before that scenarios may indeed be an appropriate and useful way to encode meteorological knowledge. One obvious advantage is that by using scenarios, one can know (and tell others) when during the day decision points are likely to occur. I imagine this would be highly valuable in the environment at the Space Center.

3. I had not expected to hear such positive feedback from the AWS. Col. Maderia said that TWFES would "help us in our weakest link," i.e., provide guidance to forecasters about what to attend to. So perhaps TWFES actually <u>can</u> help in operations, even though operational considerations were considered, in my view, far too late in the development cycle.

4. The validation question is a difficult one, as we discussed at the end of Phase I. Col. Maderia said he would not foist unvalidated scenarios on his people, but I wonder whether he might not be persuaded to. After all, the current scenarios have the imprimatur of Roger Pielke, and are not likely to be greatly in error. Perhaps more important, the consequences of error may not be great. That is, TWFES would simply suggest to the duty

forecaster that he attend to a less-than-optimal piece of data. That's something that probably happens a lot anyway. Perhaps a study of the likely consequence of (subtly) incorrect scenarios might be more useful in the short term than an attempt to fully validate everything.

5. I was interested to hear the operational needs expressed by the AWS personnel. In general, those needs were far afield of what TWFES has been designed to do. As I heard it, those needs include (1) help in distributing advisories; (2) automatic data ingest from the CYBER; (3) automatic or semi-automatic generation of terminal advisory forecasts; (4) combining the many hardware devices in the forecast center; and (5) automated help with the morning convective outlook. I can only wonder how the TWFES project might have been different had these needs been addressed earlier in the project. As it stands now, these are generally non-trivial tasks. Addressing these tasks would take the TWFES project in quite new directions, and none of those tasks (except automatic data ingest) build on any of TWFES as it exists today.

6. I am concerned at Francois Gadenne's comment that 54% of the cost of the Dipmeter Advisor project went into the user interface. This is a part of TWFES that has not yet been addressed. So we can assume that the development of working system will cost an amount equal to what has already been spent. This would be without addressing the needs 1 through 5 mentioned above, and without putting any effort into validation. That means a substantial sum will be spent to address only a single (albeit major) need of the AWS forecast office.

Now for the answers to the specific questions you posed:

1. Regarding the general approach of TWFES. The scenarios are a good way to represent meteorological knowledge. However, I still believe that the lack of probabilities is a defect, particularly for "trigger out" events.

2. Regarding the current content of TWFES, it seems pretty good. Roger Pielke is persuasive.

3. Regarding the current status of the project, it is not nearly as far along as I would have expected. The project suffers from not having had adequate input from the potential users early on.

4. Regarding current limitations of TWFES, the biggest is that there is no user interface yet. Also, scenarios haven't been validated, and the importance of different kinds of errors in the scenarios is not yet known.

5. Regarding possibilities for the future, the scenario structure is a good one for capturing meteorological knowledge. It is the only expert system structure I know of that is inherently temporal. It may not be so natural a structure in other subject areas. This argues for staying in the meteorological domain.

Regarding the "hard questions" you posed...

1. Is TWFES different than a check list? Yes, particularly because of the temporal nature of scenarios, automatic data ingest, possibility of saving and analyzing user responses.

2. Is it AI? Of course. I think anything that attempts to put verbal intelligence on a computer is AI.

3. When will TWFES be useful? Given the past and current productivity in the TWFES project, I think another $300K - 500K will be necessary to make TWFES operationally useful.

4. Is the absence of probabilities a weakness? I think so. A variety of slightly different scenarios can mimic the effects of probabilities, and these may be easier to knowledge engineer. The absence of probabilities will ultimately lead to a less robust system, I believe.

As a final recommendation I can only say that, although the amount that remains to be spent for TWFES to be operationally useful is substantial, the investment to date in developing knowledge and software is also substantial. NASA is apparently committed to continued development of the software. That being the case, I think continued development and validation in the weather area is appropriate, assuming that cooperation from AWS is forthcoming.

I hope these comments are useful to you. I will be happy to discuss further any of the points I've raised. Please keep me informed of the continued progress of TWFES.

Sincerely,

Bill

William R. Moninger

WORKING MEMORANDA

M E M O R A N D U M

TO: F. Gadenne **CASE:** 55855 **DATE:** 07-02-87 **PAGE:** 1

SUBJECT: TWFES Knowledge Acquisition

This memorandum completes the contractual requirements for Task 12 of the May 22, 1987 workplan. It is based, in part, on conversations with Art Beller during the week of June 15-19.

<u>Overview</u>

This note summarizes a general methodology for using the TWFES Scenario Editor (SE) to construct a scenario-based knowledge base of weather phenomena. It is assumed that the weather phenomena of interest do not include summer thunderstorms (the original subject of TWFES), and that the prospective expert forecaster is completely unfamiliar with both the SE and the concepts behind TWFES.

First of all, it should be recognized that the SE has been designed so that it may be used, unattended, by a non-programmer. To the extent possible, all forecasters who use the SE should be encouraged to experiment with the SE facility and grow comfortable with it so that they require little or no guidance in its everyday use.

The basic aim should be the elimination of the need for intervention by a knowledge engineer. This process might take anywhere from several months to several years, but nevertheless it should remain the ultimate goal of SE use.

It must be recognized, of course, that the SE runs on a Symbolics computer, and that there will be many user anxieties associated with growing accustomed to the complexity of the Symbolics user interface. More importantly, it must be recognized that, even though the SE has been designed for use by non-programmers, the creation and specification of scenarios is fundamentally a programming-like task, albeit a high-level one. That is, a fully-developed scenario is very much like a complex computer program which is written in a curious, special-purpose computer language. Specification of scenarios is, therefore, a structured task which requires the use of a specific syntax, and can be quite difficult, even for seasonal computer programmers.

It turns out that very few forecasters have ever attempted to record their knowledge in a structured fashion. They are typically not accustomed to thinking introspectively, and will almost universally have a difficult time making this type of conceptual shift. On the positive side, most forecasters are quite talkative (about the weather, at least) and are, on the whole, an extremely pragmatic group. In addition, forecasters are painfully aware of how perishable the experimental knowledge is which is the focus of TWFES' scenario-based architecture. Once they are familiar with the SE's operation, most forecasters will probably welcome the opportunity to use such a tool. Finally, forecasters have been faced, during the past several years, with increasing computerization of the forecasting environment, and are generally comfortable with learning the use of a new computer-based forecasting tool.

We will now review some general principles of SE use. We then turn to a structured procedure which may be followed over the course of a year or more of knowledge acquisition.

General Principles

Numerous in-depth conversations with forecasters have revealed that they normally move from synoptic to local-scale phenomena when describing their scenario-like weather experiences. Large-scale events set the context for small-scale events, and local weather can rarely be understood without first considering the large-scale environment in which it occurs.

This large-to-small transition implies that all scenario-related knowledge acquisition should proceed similarly. That is, first one should consider the largest spatial scale appropriate to the particular scenario, and move to smaller scales only when the larger scales are more or less well-understood. Note that the ordering of a scenario's events should be such that large-scale events precede small-scale events. Such an ordering parallels the way a forecaster actually operates and will "feel" natural to him or her.

From a practical standpoint, if one assumes that scenario specification is performed in several cycles of building, testing and modifying, the first attempts at specifying a scenario should concentrate on larger-scale phenomena. Specification of smaller-scale phenomena should be cursory at first, with details being filled in at a later date.

Concerning the various pieces of a scenario's structure, the concentration on large-scale phenomena implies that initially one should focus on trigger events and the first few events of a scenario. Later events, which typically address localized weather features and their evolution in real-time, may be sketched in at first and elaborated upon at a later date.

During the entire process of scenario specification, it is critically important that the forecaster focus on the precise connection between hard data and the detection of recognizable signatures in that data. Gradually the attention of the forecaster should be turned to the detection of high-level weather features which are specifically mentioned in a particular set of events. Again and again the forecaster should return to examples of actual data in order to explain how (and why) certain features should be detected.

This bottom-up approach of proceeding from raw data to high-level weather features contrasts directly with how scenarios are initially conceived, which basically involved a top-down process of proceeding from a scenario to its constituent events and the ordering of those events. The conflict between these two approaches is a rich source of creative energy and should be exploited whenever possible. Juxtaposition of the two approaches, and freely mixing them over the course of a several-hour session, is highly encouraged.

Finally, it must be recognized that the scenario-based approach is fundamentally a phenomenological one, and makes no attempt to explain "why" the weather occurs the way it does. The aim of using the SE is not to write a treatise on meteorological physics. Rather, the SE should be used to encapsulate the behavior and evolution of well-recognized weather features, and to capture the details of how one detects and monitors those features using readily-available data sources.

Put another way, a scenarios construction may be thought of as specifying:

- Who: features
- What: events
- How: analysis of data sources to detect and monitor features
- When: event ordering and relative timing
- Why: ignored

The only exception to "why" being ignored possibly lies with a scenario's trigger events. At run time, knowing "why" a scenario is currently active simply requires identifying its triggering event(s). This is not, however, the usual sense of "why" as used in the Artificial Intelligence literature.

TWFES Knowledge Acquisition Procedure

It is clearly impossible to provide a recipe-like procedure for using the TWFES SE. Using the SE for knowledge acquisition requires a subtle and sensitive approach. Because the SE is designed to be used directly by the expert forecaster, with little outside help, the role of the knowledge engineer is primarily to guide the forecaster rather than elicit scenarios through clever questioning of the expert.

Moreover, the SE has been designed so that knowledge can be added at all levels simultaneously, therefore, use of the SE can be somewhat opportunistic, with small "snippets" of information being added as they occur to the forecaster.

Nevertheless, there is a distinct ordering of SE-related activities which has proven useful in the past. Some of this ordering reflects simple common sense, while other parts of the ordering may not be immediately obvious.

In any event, one may divide the basic sequence of SE usage into three broad categories:

- SE Training
- Historical Retrospective (off-line)
- Observation Testing (on-line)

These three categories are described separately below.

Training

The type of training which comes first is in the mechanics of using the SE. It is not necessary at this point for the forecaster to understand fully the scenario architecture, nor why the information is gathered (in the SE) precisely as it is. Rather, in the beginning one should concentrate on making sure the forecaster understands the basics of the Symbolics interface, including menus, who-line and so forth.

Once the basics of the Symbolics interface have been mastered, make the forecaster familiar with the SE text screen. Illustrate the connections between scenarios, events, features and data-sources using existing examples. Teach the forecaster to "navigate" through an already-built scenario, including mastery of browsing a scenario graph.

Next, build a simple test scenario (in the new weather domain) from just a few simple events. Insure that each event refers to a specific feature or features, with each feature being built and described from scratch. Experienced with defining new time windows and reordering the scenario's event tree. All of this should be done using only the SE text screen.

After this, turn attention to the SE map facility. Begin by illustrating how the various types of map features may be defined and edited. Define a map feature and show how it looks at various geographic scales. Returning to the text screen point out the connection between already-defined features and the different types of graphic objects supported by the SE. Define graphic-object types for the features identified in the test scenario above.

Returning to the map, bring up the test scenario and define simple graphics for its events. Show how graphic changes may be defined for different tasks (for a single feature) and how these changes define a cartoon-like sequence of images which are somewhat analogous to a satellite loop. Experiment with the map-related graphics for the test scenario.

Now allow the forecaster an extended period of browsing through existing scenarios. Encourage the forecaster to choose one or two scenarios and study them in-depth. Have the forecaster make his or her own modifications to those scenarios (but not save them!).

Ensure that the forecaster follows all of the events in a scenario back through the object hierarchy to the appropriate data sources. Ask the forecaster to ponder how advice should be structured at run-time, given that a particular event is being monitored in a scenario.

By extended browsing, through the existing set of scenarios, the forecaster should begin to have a good grasp of how a scenario is structured and why it is structured in such a peculiar fashion. The forecaster should have learned (by example) a considerable amount concerning the scenario-based architecture.

Now is the time to review with the forecaster, in detail, exactly how the scenarios will be processed at run-time. Presumably the forecaster will have seen at least a cursory demonstration of the run-time TWFES. Give an extended demonstration. Work through several test-case days in displaced-real-time mode. Show exactly how the contents of the scenario knowledge base (in the SE) are reflected in the TWFES run-time output. Flip back and forth between the run-time system and the SE. Spend several days on showing the connections between the two.

The time to complete the training described above should total anywhere from five to twenty days of forecaster time. Approximately half of that time should be spent by the forecaster using the SE alone, with no assistance. Interface-related difficulties should be noted and discussed in detail between the forecaster and knowledge engineer.

Historical Retrospective

The next stage of SE use may be thought of as "off-line" in the sense that it involves the construction of scenarios based solely on historical data and the forecaster's personal memory.

The first step entails the detailed review of historical records. These records, if available, should contain enough information (about each individual day) that the forecaster has no difficulty reconstructing precisely what happened on those days. Ideally, the days should coincide with days on which the forecaster was on duty, in order to provide a more realistic historical setting for reviewing the various days. A minimum of a few dozen historical days will be required for this activity.

The knowledge engineer and forecaster now review the "events" of each day in considerable depth, spending at least one-half hour per day. Examine relevant data, with the aim being the identification of the primary weather features and event types which were involved. Assemble a short textual description of each day for later use.

Once the historical review is complete, it is time to construct tentative scenarios based on these records. To the extent possible, ensure that the scenarios cover all of the historical days. Keep in mind that the scenarios represent generic weather behavior, as the forecaster will almost certainly have an initial tendency to make the scenario too specific.

At this point in the scenario-building exercise, there is little need for precision: the main goal is the identification of weather-behavior types, i.e., scenarios. Recall the above comments concerning the large-to-small sequencing inherent in scenario specification. Concentrate on the details of large-scale weather patterns at this point, leaving precise specification of small-scale features to alter analysis. Work out scenario-trigger logic at this time, also.

Once an acceptable set of preliminary scenarios have been constructed, the next step requires in-depth review and modification of those scenarios. Using the actual historical data, "play out" (manually) each day against the set of scenarios just constructed. Concentrate on event timing and the extraction of relevant features from raw data. Make any needed modifications to the large-scale events which were specified previously. Extend the level of scenario detail down to the local-scale phenomena.

Now it is time to consider the scenarios as an integrated set. Explore the need for sub-scenarios which may be common to multiple event sequences, particularly large-scale sub-scenarios which might trigger the monitoring of several small-scale sub-scenarios. Insist that the geography of each scenario be made explicit by constructing a map-based set of graphics for each scenario. Define any new map grahics which may be required at this time.

The final step is for the knowlege engineer to make the various events computable. That is, the event predicates must be specified. For each event which can be confirmed automatically from available data, predicate specificaton requires the writing of a procedure to be invoked whenever the events occurrence is to be tested. For those events which cannot be tested automatically (i.e., have no predicate), the forecaster must provide detailed event-level comments which will be sufficient for another forecaster to understand, at run-time, precisely what is required for that event to occur.

If enough time is available, once the scenarios are in a reasonably-complete state, they should be loaded into the run-time TWFES and executed manually against the historical data. It is optional as to whether simulated MIDDS data is prepared for the various days; this simulated data would be quite useful for predicate testing, for example, as well as providing a more realistic run-time testing.

The above retrospective stage of SE use can be quite lengthy. A conservative estimate is to allow at least three days of work for each historical day. The total time, assuming a few dozen historical days, should therefore come to several months of calendar time. Since the following stage of SE use entails the testing of the new scenarios, it will be most useful if the above activities take place in the (meteorological) "off-season" which immediately precedes the season in which the new scenarios are expected to occur; this timing will minimize the lag between the specification and testing of the new scenarios.

Observational Testing (on-line)

The next phase of SE use involves observational testing of the scenarios, described above, whose specifics are based only upon historical evidence. This testing takes place during the season in which one expects to observe the just-completed scenarios. The testing may be expected to require the entire season.

In addition to the testing of existing scenarios, this phase of SE use also involves the construction of new scenarios. The new scenarios will be based upon intensive observation of the weather during an entire season, by the SE-trained forecaster, with an eye towards the consruction of new scenarios.

The first step is to have the participating forecaster maintain a daily log of how the weather evolves each day. Here the forecaster will use the SE, as a sketch pad of sorts, to record significant weather events as each day unfolds. The end result will be a set of "scenarios," one for each day, which cover the entire test season. These scenarios will provide the raw material for the next round of knowledge engineering, described below.

In addition to daily logs, the forecaster will also collect a data set for each day. Each data set must be of sufficient detail to test scenarios using the run-time TWFES in displaced-real-time mode.

In addition to the maintenance of a daily log, the forecaster should also informally monitor the daily progress of the previously-completed suite of test scenarios. Because of the tentative nature of the scenarios by this point, it is NOT necessary to test the scenarios formally by running them through the run-time TWFES. In fact, such rigorous testing would be counterproductive, since the scenarios will almost certainly be incorrect, and the psychological damage (to the forecaster) might be severe. Whatever the case, the informal testing should concentrate on the smaller-scale weather phenomena (presumably only fleshed out in the preliminary versions) as well as real-time data monitoring and feature recognition.

The next step of the observational phase of SE use involves the genralization of the daily logs maintained by the forecaster. It is up to the project team as to when to begin this generalization process. One school of thought says that one should wait until the end of the season so that all available information has been gathered. Another school of thought says that it is wise to begin the process almost immediately. In any event, here the idea is to generate new scenarios by collapsing the daily logs (which, after all, will have been formulated as scenarios to begin with) into only a few discrete scenarios. The new scenarios may be sketchy at first, and largely ignore local, smaller-scale phenomena. The important thing is to identify the major types of weather behavior being observed, NOT specify a set of scenarios in great detail.

The detailed specification of the new scenarios is delayed until the end of the observation season. At this time, the knowledge engineer and forecaster should work closely to fill in the scenario details ignored during the observational period: event timing, feature extraction from raw data, and interconnection of the various scenarios. Substantial modification of the original (historically-based) scenarios, however, need not wait until the end of the season.

The next step of this observational phase requires the knowledge engineer to make the various event predicates computable. This process is virtually identical to the previous session of making predicates computable (see the "Historical Perspective" section above). The main difference will be that the weather events described in the new scenarios will fresher in everyone's mind, thus making the predicate-programming task considerably easier.

The final step is to take the (computable) new scenarios and test them, using the run-time TWFES in displaced-real-time mode. Use the data sets collected by the forecaster during the observational season. As a conservative estimate, assume it will require one week of effort to test and modify each of the scenarios; this estimate should be valid for both the original (historically-based) and new (observationally-based) scenarios.

Assuming the scenario-specification process has been successful, the next step is to test the scenarios operationally. This operational testing, of course, will likely have to wait for nearly one year before commencing because of the need to wait for the appropriate season. This should impose no unnecessary delays, however, as the project team will almost surely need that much time to arrange for automatic data feeds, forecaster training, and so forth in the operational forecasting facility.

M E M O R A N D U M

TO: F. Gadenne | CASE: 55855 | DATE: 07-02-87 | PAGE: 1

SUBJECT: Other Use of Scenario Concept

This memorandum satisfies the contractual requirements of Task 26 of the May 22, 1987 workplan. It is based, in part, on conversations with Art Beller during the week of June 15-19.

<u>Overview</u>

The scenario-based architecture of TWFES is a general-purpose scheme which may have a variety of application within NASA other than weather forecasting. There is nothing in the TWFES architecture which permanently weds it to weather phenomena, other than the particular objects (weather features) which are the subject of TWFES. In fact, there is every reason to believe that a scenario-based architecture would prove useful for a large number of applications where time-dependent reasoning is critical.

It should be pointed out that a simple precursor to the TWFES architecture has already been used in an application developed by Arthur D. Little, Inc. (ADL) for a major manufacturer of specialty chemicals. The subject for this application was the operational control of a complex proess facility. The aim of this particular system was to avoid situations in the process facility which were sufficiently dangerous to require shutting down the facility. This process control application is, therefore, similar in its goals to the TWFES application, in that TWFES is also concerned with timely anticipation and avoidance of a potentially-dangerous situation at KSC: unexpected lightning.

The ADL client vigorously pursued the above application after ADL had completed its portion of the project. For historical reasons, the process control application was ported to the Picon system. The temporal-reasoning facilities proved so useful that Picon's developers then incorporated the underlying architecture into Picon's general architecture.

In the past, ADL has identified other possible applications for a scenario-based architecture. These possibilities include stock trading, auditing and intelligence-gathering.

Given the possibilities for widespred application of TWFES' scenario-based architecture, it seems appropriate to review the basic characteristics of those situations where a TWFES-like architecture might prove useful.

Characteristics of the Expert

The ultimate source of scenarios lies in the experiences of human experts. The major characteristic of experts should, therefore, be that they have learned their job largely by on-the-job training experience. This implies that one of the distinguishing traits of experts should be that they have a great deal of direct, personal experience in performing their job. Other factors being equal, someone with more experience should be preferable over another individual with less experience.

A second characteristic is that the experts have little formal training in their area of expertise. The lack of formal training genrally indicates a heavy dependence on personal memory, and that the development of expertise is an inductive process. Since the TWFES architecture reflects a purely phenomenological approach, with no attempt to capture causal mechanisms, it is particularly well-suited to a situation where formal training is of limited value.

The stress on personal experience brings us to another characteristic of experts in such a situation: The very best experts will have the very best memories. Typically, these memories will be of particular problems which arose and the specifics of how those problems were solved. The job of the knowledge engineer then becomes one of generalizng these specific memories into the generic behaviors as represented by scenarios.

Characteristics of the Task

A task which is amenable to support by a scenario-based system will also have a number of distinguishing characteristics. It must be recognized that a primary aim of a scenario-based system will almost certainly be to focus the attention of the user on a limited subset of the data which is available to him or her. In other words, the monitoring of individual scenarios will define a context for the user which acts to point out the most significant types of phenomena to be expected at some specific time.

Given this ability of a scenario-based system to focus attention, one task characteristic will likely be that a large quantity of data is being assimilated by the user. Typically, the quantity of data will be sufficiently large that the user has little or no chance of analyzing all of the data. This implies the need for a mechanism which can isolate those aspects of the data which are the most significant, something which is ideally suited to a scenario-based architecture.

A related task characteristic should be that task performance is time-critical. That is, the task should call for making rapid decisions, preferably in situations where it is impossible to perform sufficient analysis to be certain of the decisions' correctness. Preferably, the task should be performed under heavy outside pressure; this will reinforce the need for user support.

The supported task will likely have the characteristic that the user is responsible for monitoring a large number of observational details. These "details" might either consist of a large number of individual data sources (see above), or might be administrative in nature. Whatever the case, an additional feature of the task, which would make a scenario-based architecture useful, is that it involves a large number of distracting interruptions. Numerous interruptions imply that the person(s) performing the task probably have a difficult time maintaining a coherent train of thought in the face of disruptions; the hypothesis-tracking nature of a scenario-based architecture would likely be highly useful in such a situation. If it is the case that the task-related monitoring requires "continuity" over a period of several hours or more, so much the better for a scenario-based approach, since there will be the additional interruptions caused by shift changes, with a corresponding need for inter-shift transfers of knowledge between those going off and on shift.

A final task chracteristic, somewhat related to those mentioned above, is that the system being monitored by the user should be relatively ill-understood. If this is the case, it will imply that a phenomenological approach is appropriate. More importantly, it will reinforce the need for long, task-specific experience before competency is reached. Such a combination will partially justify the scenario-based approach's concentration on "what" and "how" rather than "why."

Potential Tasks

A number of different tasks come to mind when considering the match between the TWFES architecture and the types of tasks performed by NASA employees at KSC.

One possibility lies in launch processing, where test engineers man control boards which monitor potential mechanical problems prior to launch. In this situation, much of the knowledge which exists is empirical in nature, and a great deal of direct experience with the control boards is required of the test engineers before they reach competency. Moreover, this particular task involves the monitoring of specific phenomena over periods ranging from a few minutes to many hours.

Another possible task which might benefit from the support of a scenario-based system lies in the area of satellite control. The controllers who perform this task are required to make high-pressure decisions based upon very little data, with very little time being available to make those decisions. Moreover, like launch processing, long experience is needed before competency is reached. Finally, again like launch processing, much of the knowledge which exists is experimental in nature, and quite difficult to capture completely in the form of general principles.

A more general area of application for a scenario-based scheme is that of monitoring and modifying schedules or plans for autonomous or semi-autonomous systems. Here the idea is that a plan is created for some type of autonomous system, which is then translated into scenario form. The events of the "scenario" then become individual tests which either confirm or deny the satisfactory execution of the plan. Such an approach allows for considerable flexibility in precisely how the system's progress is tracked. Moreover, it is especially useful in those situations where the system is semi-autonomous rather than completely autonomous, since the memory-enhancement capabilities of a scenario-based system could allow a single person to handle a much larger number of systems than might otherwise be possible, by focusing the handler's attention only on those systems which require attention at the current time. This particular applicaton area is, of course, much more speculative than the others, but it is probably very worthwhile to explore the possibilities because of the tremendous payoffs which are possible.

FROM: Bob McArthur /pjt BLDG/ROOM: 35/341 EXT: 2903

M E M O R A N D U M

TO: F. Gadenne CASE: 55855 DATE: 07-02-87 PAGE: 1

SUBJECT: TWFES Testing Methodologies

This memorandum completes the requirements of Tasks 7 and 10 of the May 22, 1987 workplan. It is based, in part, on conversations with Art Beller during the week of June 13-17.

TWFES Testing

There are two types of testing which might be applied to TWFES. The first concerns itself with software quality from an engineering standpoint. Typically such testing is used to ensure that successive versions of a program perform at least equally well on identical problems, and that the newer version does not introduce new problems not previously present. This type of testing is not of interest here.

The second type of testing is concerned with measuring the operational value of TWFES. It may be considered a question of experimental design, as such testing attempts to answer two basic questions:

- What is an appropriate metric of TWFES' operational value?
- How does that metric vary between two groups of forecasters when only one of those groups has access to TWFES?

Performance Metrics

Devising a metric which adequately measures the value of a forecaster-support system is no trivial task. In fact, it has a long and bitter history in the annals of operational forecasting. The National Weather Service, for example, has spent several years and many millions of dollars attempting to measure their improvement in forecasting accuracy as the result of introducing increasingly-elaborate numerical models of the atmosphere. Briefly put, the results are inconclusive and contradictory, even given the extraordinary amount of effort put into this testing program, since skeptical NWS critics have consistently accused NWS of constructing artificial metrics which give a misleading impression of increasing forecasting accuracy, when in fact there is much evidence that NWS forecasting has not significantly improved during the last twenty years.

In any event, the narrow operational focus of TWFES allows us to identify at least four separate levels of performance metrics:

- Dollars and safety,
- Lead time for lightning warnings,
- Similarity between TWFES advice and forecaster actions, and
- Meteorological correctness.

Ultimately, of course, one would like to measure TWFES performance in terms of dollars saved and increased safety. The dollars saved fall into two categories:

- Elimination of unwarranted schedule slippages, and
- Avoidance of equipment loss.

Increased safety is more difficult to measure directly, but is, in principle at least, concerned with preventable loss of human life and injuries due to adverse weather conditions.

It seems likely that it will be exceedingly difficult to measure this type of operational value in a consistent manner. The most one can hope for is probably a series of anecdotes which highlight specific instances of how TWFES use prevented a specific schedule slippage or equipment destruction. This may be more than sufficient, however, because of the high costs associated with schedule changes and equipment loss at KSC. Indeed, a decrease in delays of only a month or two is probably more than sufficient to justify the cost of developing and deploying TWFES.

Measuring lead time for lightning warnings, on the other hand, should be much more straightforward. First of all, it is the primary measure whereby the USAF and NASA judge forecaster performance. Lead time is carefully tracked and recorded by every duty forecaster at CCFF, and forecasters are quite accustomed to being judged on that basis. Lead time is also a very clear-cut metric which can be statistically analyzed in a relatively simple fashion. Moreover, there is obviously a relationship between lead time and dollars saved, even though the details of this relationship are not known precisely.

It should also be possible to measure the similarity between TWFES advice and forecaster actions. Here the TWFES "advice" would consist of the data sources it recommended as being of interest. One would then record the activities of an experienced forecaster (in particular, the data sources that forecaster was monitoring) and compare the two. Using such an approach, it should be possible to get some idea of how closely TWFES mimics the thought processes of experienced forecasters.

The chief difficulty with this metric is that of recording forecaster activities. Presumably one could simply record the MIDDS screens requested by the forecaster over a period of several days or weeks, but this technique ignores a number of data sources which are not available through MIDDS.

Finally, it is possible to consider measuring TWFES meteorological correctness by answering the following sorts of questions:

- How many days failed to trigger any scenario?

- Of those scenarios which triggered, to what degree did they complete?
- For those scenarios which "failed" (by being abandoned when they should have completed), what were the reasons?

In other words, this type of testing would treat the TWFES scenarios as forecasts and attempt to measure their success accordingly. Such testing, however, is really of little interest (other than purely academic) since TWFES has not been designed to issue forecasts autonomously. Rather, it is intended to be a support tool which guides the forecaster as to which phenomena are of interest at the present time. Thus, it is the combination of forecaster and TWFES which should be judged, not TWFES as an isolated entity.

Measurement of Operational Value

Now we turn our attention to the question of how to measure TWFES operational value, assuming we have already decided what to measure.

The basic problem is the lack of a control group. That is, ideally we would set-up two separate forecasting groups, one with and one without access to TWFES advice, and measure their relative performance. Moreover, to be scientifically accurate, the availability of TWFES should be the only difference between the two groups.

Simply identifying two identical groups of forecasters would be difficult enough. Presumably the two groups should be drawn from the ranks of inexperienced USAF duty forecasters, since it is this group which stands to benefit the most from TWFES use. Even assuming the existence of the two groups, there is then the problem of arranging the necessary time for them to participate in the test. Such participation would be quite time-consuming and might require a higher degree of involvement than the USAF is willing to allow.

Finally, there are the logistical problems associated with providing identical forecasting facilities to the two groups. Conceivably one could simply provide each group with identical MIDDS workstations, but this sidesteps the problems associated with access to non-MIDDS data sources. That these logistical problems are large may be seen in the extraordinary efforts made by the PROFS program in setting up their testing laboratory; here we find that NOAA actuallly spends more money on testing the PROFS system than they do on developing it.

Assuming, for the moment, that it is uneconomical to arrange for TWFES testing according to rigorous experimental principles, what might be acceptable?

One alternative is to train only a small number of duty forecasters in the use of TWFES. TWFES would then be made available in the CCFF for use by those trained forecasters, but no others. TWFES use could be monitored, and its output compared, at least informally, with forecaster actions. Finally, an assessment would have to be made at the end of the period as to whether TWFES use had a positive operational impact. Again, we stress that TWFES use will be most beneficial to novice duty forecasters, and to the extent possible, they should be the ones who participate in the testing.

Another alternative is to make TWFES available only to the CCFF station chief. Under this set-up, the station chief would be responsible for comparing TWFES output with the activities of novice forecasters, and determining the extent to which those novices might benefit from TWFES use. It is likely, however, that the CCFF station duet already has sufficient responsibilities, and demands on his time, to make the addition of TWFES use an unacceptable burden.

In any event, whatever the testing procedure, the ultimate test of TWFES' operational value will be the desire of duty forecasters to use the tool. Ultimately, the meteorological correctness of TWFES may be irrelevant. It may well be that TWFES' advice is rarely heeded (or even correct), yet it provides valuable guidance to the forecaster concerning what weather phenomena are currently of interest. Whatever the case, the placement of TWFES in the CCFF for a single thunderstorm season cannot fail to generate numerous improvements to TWFES, both in scenario content and user interface details, which are impossible to obtai ı otherwise.

TWFES Testing Methodology

This document will describe our initial work at establishing a testing methodology for TWFES. Testing knowledge-based systems differs from validation and verification of conventional systems. For our purposes, we have defined validation as the process of answering the question "does the system meet its intent, were the specifications any good?" Verification we define as the process of scoring various aspects of the system; does the system meet the specifications?In addition to checking input/output verification and validation, one must also test <u>how</u> the system arrived at its output; what were the reasons behind the output.

The testing methodology has two phases. The first phase (summer of '87) tests the knowledge of weather scenarios used by the system. The second phase (summer of '88) tests the performance of TWFES in its operational niche.

Phase I: Testing in the CIF, Summer of '87

<u>Assumptions</u>

This phase of the testing assumes that a testable run-time version of TWFES will be initialized with morning sounding data from 5 stations. Initialization will be static, not dynamic (does not take into account the "data fields"). Real-time data feeds (those occurring periodically) are yet to be decided, but will include mesonet winds. Other systems available in the CIF will be:

- Video Cameras
- LLP
- Field Mills
- Mesonet
- Power Heliometer
- Satellite via TV
- GOES Satellite Imagery
- Radar
- NO MIDDS

There will be at least 12 scenarios in the testable run-time version of TWFES, and data logging (putting together the data pecks for every day) will be carried out throughout the summer. The test period runs from mid-May to mid-September. The following staffing is anticipated.

Jeff Smedley	7/7 (7 days out of 7)
Jim Nicholson	1/7
Art Beller/Pam McVeagh	2/7
ADL	TBD
Dave Helms	5/7
CCFF Personnel	1/7

It is also anticipated that staff in the CIF will be called on to give demos of TWFES to visitors.

Goals

The following goals have been established for testing in the CIF during the summer of '87.

1. Develop a knowledge refinement methodology; determine data logging requirements.

A. Real Time Scenario Refinement Methodology

TWFES will be operating in the CIF using static initialization procedures and real-time data. Scenarios in the system will be "matched" against each day as it unfolds. The aim is at least to find a day for every scenario, and to find or develop a scenario for every day. Schematically, the process can be represented as shown in Chart 1.

Data logging requirements for each actual day are:

a. daily log

b. satellite

c. radar

d. LLP

e. mesonet

f. sounding data

System logging requirements for TWFES are:

a. all events recognized

(to be put in a DRT data set)

i. data values of features

ii. data source for value

b. version of TWFES being run

i. translated scenarios

B. <u>Displaced Real Time Scenario Refinement Methodology</u>

TWFES can be operated using Displaced Real Time Data (DRT).

The process for evaluating TWFES using DRT data is as follows:

1. Initialize TWFES using DRT.
2. Look at scenarios activated.

   which, how?
3. Look at scenarios not activated.

   which, why?
4. Play the day.

Evaluate events as they unfold, as they trigger in and trigger out scenarios.

5. Output.

   detected, localized problems.

The repair process for TWFES will be to:

1. Work from a diagnosed problem.
2. Change the affected scenario.
3. Verify the repair by replaying the day.
4. Update the scenario file.

It should be noted that the process of knowledge refinement is qualitative throughout. When an actual weather day fails to match any TWFES scenarios, it will be left to the judgment of the project weather forecasting expert(s) whether to adjust an existing scenario to accommodate the day or to create a new scenario.

2. Generate Data Sets

When time permits, a facility will be developed for editing data sets to create DRT data sets. The aim is for the system to be able to be run in displaced real time, where the "play-back machine" will have the ability to jump through time.

3. <u>USAF Involvement</u>

Air Force personnel will be encouraged to participate in TWFES testing in two ways. First, a paper graphical display of scenarios will be made available to forecasters in the CCFF. Results of daily initialization (i.e. - active scenarios for the day) will be telephoned to the CCFF in the morning so that duty forecasters can compare the actual unfolding of events with those anticipated by TWFES. Second, Air Force personnel will have access to TWFES in the FCTB (Flight Crew Training Building) and will be encouraged to enter their own scenarios or run the existing scenarios in DRT.

4. <u>Extend WFES to Run in Simulation Mode</u>

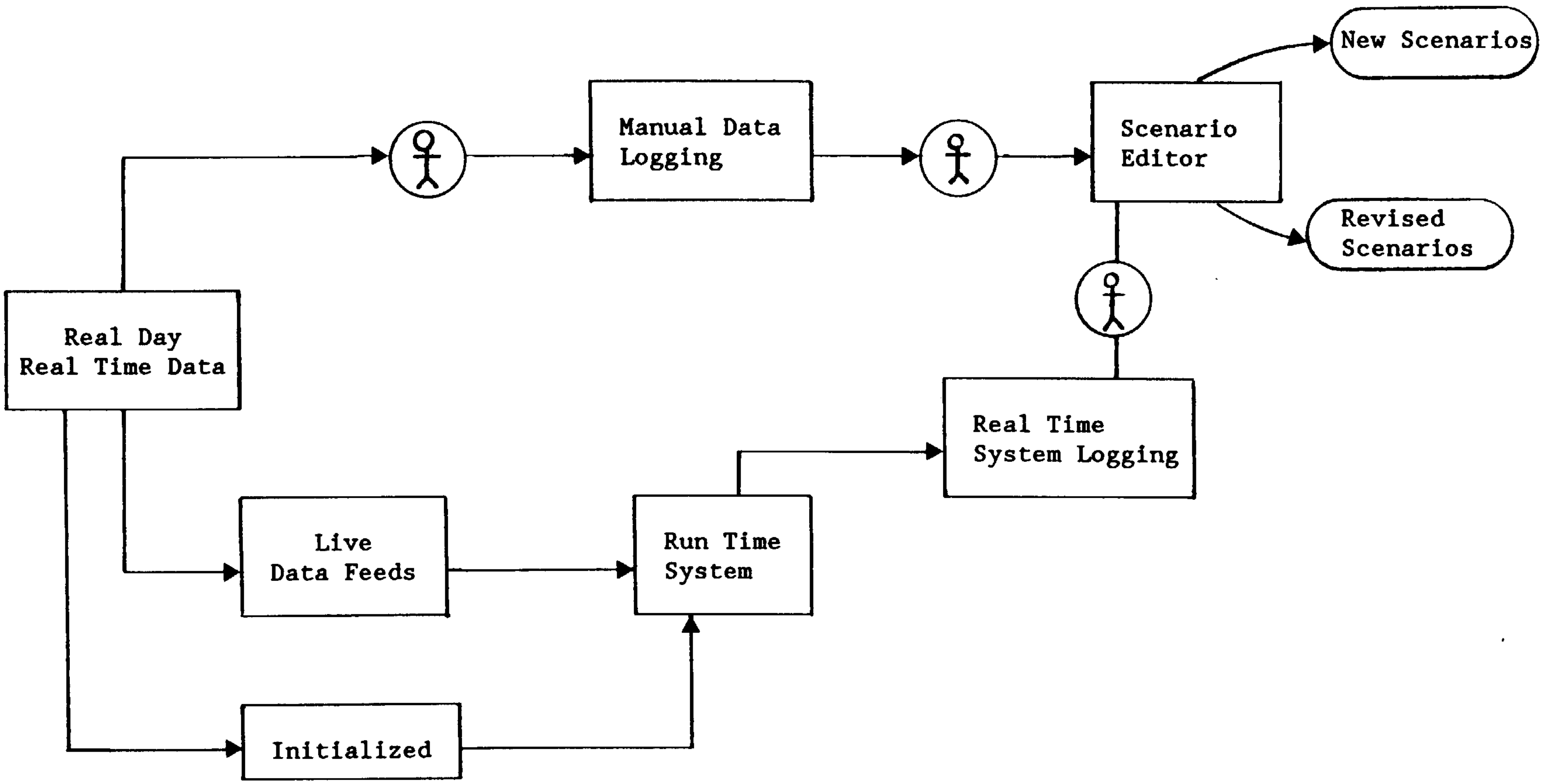
Ultimately, TWFES should be able to be run in a simulation mode, with the user in control of the clock and data values. The system would be run against a dataset to a point, then the user would have the option of supplying a new value to explore whether TWFES does the "right thing."

Phase II: Formal Testing in CCFF, Summer of '88

Methodological problems were discussed in the March status report. Further work needs to be done in this area. In order to validate the system on a cost basis, a simple model of shuttle operations must be developed, and an understanding must be gained of how weather forecasting impacts those operations.

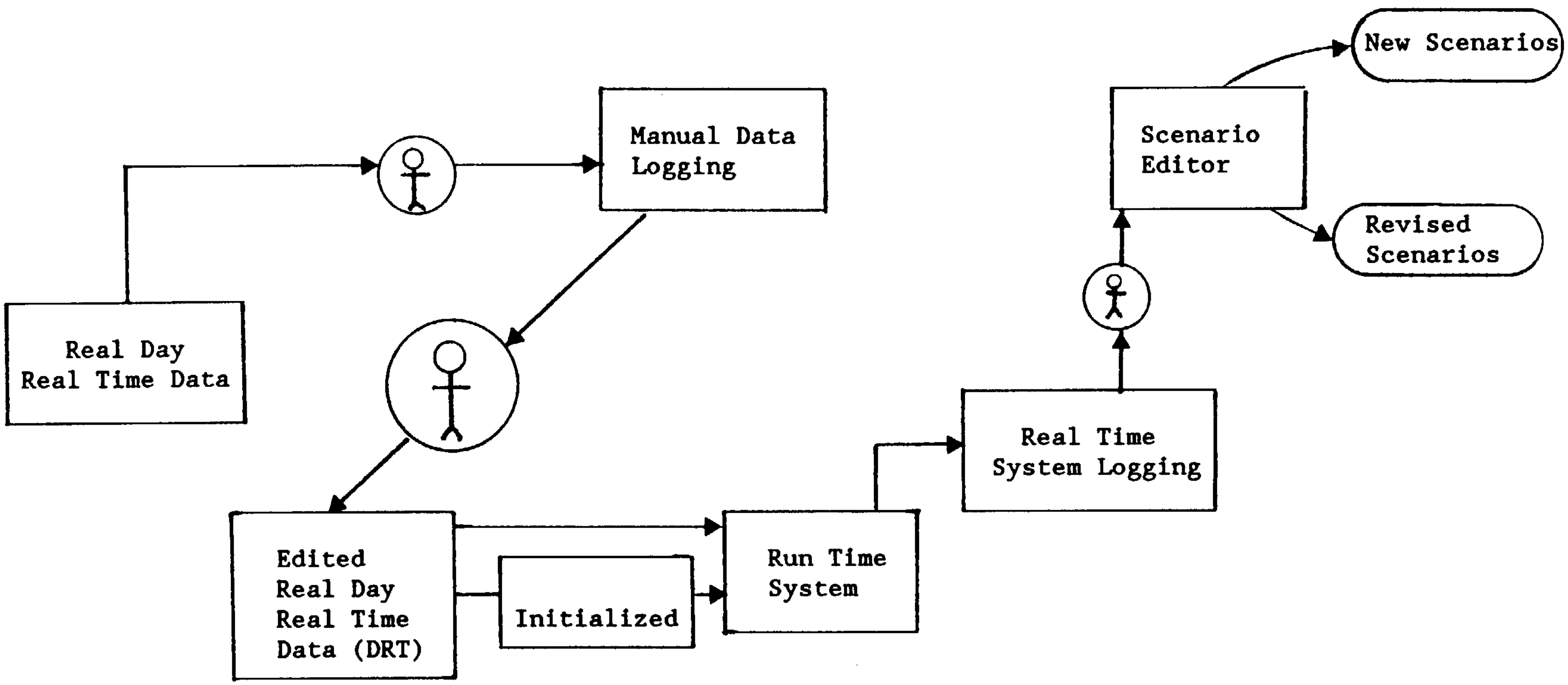
REAL TIME SCENARIO REFINEMENT PROCESS

CHART 1



DISPLACED REAL TIME SCENARIO

CHART 2



APPENDIX

D R A F T

6 Sept 1987

In-Situ Convective Activity

Study Objective:

The object of this study is to explore the qualitative and quantitative parameters that are associated with In-Situ convective activity. This study will attempt to construct a shell for the In-Situ scenario that will include the necessary moisture, KI, LI and wind velocities that are associated with In-Situ activity. The study will consciously try to set-up a system that will forecast 100 per cent of the bona fide In-Situ scenarios. This study will be limited to the amount of data that can be gathered in 2 1/2 months of observation.

This report was prepared for A. D. Little, Inc. of Cambridge, MA under subcontract C-9010-845 in conjunction with NASA contract NAS10-11333.
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1. Front End Trigger Out/In for an In-Situ Scenario

a. The operator/technician must determine if XMR rawinsonde data will be valid through 0900-1400L; if not, they must substitute upstream data that will be applicable for the forecast time period (see Appendix E).

b. Front End Trigger Out (T/O): If the answer is yes to the following then the In-Situ scenario is triggered out (T/O).

1) AS/AC/CS ceilings exist 0900-1300L;

2) Excessive directional wind shear (a change of 80 degrees/2,000 ft in vertical):

a) 3,000-10,000 ft, T/O RW/TRW

b) 10,000-20,000 ft, T/O TRW

3) Excessive mixing:

a) H8H7 WND > 17 kts, T/O RW/TRW

b) H8H7 WND > 15 kts, T/O TRW

4) Thermal/Subsidence Inversion(s) (+1.5 C/1,000 ft):

a) 1,000-10,000 ft, T/O RW/TRW

b) 10,000-20,000ft; T/O TRW

5) Convective Temperature (Tc) > 90

6) K Index (KI) < 25

7) Lifted Index (LI) > -3.0

8) Layer Averaged Mixing Ratio (w) > 15.5/8.0/2.0/0.6

(See definitions for layer boundaries.)

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2. Moisture Convergence Logic

a. Thunderstorms and rain showers need a minimum amount of moisture to form a cloud of enough vertical depth to precipitate and still greater for lightning activity.

b. Most of the moisture for convective cloud development is derived from surface to 750 mb, above which the ability for air to hold enough usable moisture is limited.

c. When moisture is limited in the vertical, the atmosphere tends to "make up" for the deficiency by focusing moisture along a narrow axis. This occurs when the steering wind has a component of flow against the sea breeze boundary (SBB) forward progress; therefore, it is possible to form thunderstorms and even more frequently rain showers along the SBB in a seemingly dry low level atmosphere. With a moderate westerly steering component the moisture parameter will be at least partially dependent on the degree of moisture convergence.

d. Conclusion: The moisture parameter for In-Situ convective activity will differ depending upon the steering winds direction and therefore it is necessary to consider each direction individually within the scenario.

1) Westerly Component (WC): > 5 kts mean velocity and > 5 kts perpendicular component to the SBB axis from the west or 250 degrees.

2) North or South Component (N/SC): > 5 kts mean wind velocity and < 5 kts perpendicular wind component to the SBB.

3) East Component (EC): > 5 kts mean wind velocity and > 5 kts perpendicular wind velocity from the east or 070 degrees to the SBB.

4) Variable Component (VC): < 5 kts mean wind velocity.

e. Order of moisture needs for a given static cylinder based on possible moisture convergence as per wind sector.

1) VC - VC has the least moisture convergence and potential cells must derive their moisture from the a limited volume of water vapor and therefore it must have the most initial moisture in the L1 and L2 layers to support cell activity.

2) SC (discussion limited to SC as NC is rare during the air mass regime) - SC has limited moisture convergence on the southern flank of the cell. Cells must develop in an atmosphere that is moisture laden which is usually the case.

3) EC - EC has marginal convergence caused by onshore speed convergence and the thermals transferring the sea breeze flow from the horizontal plane to vertical (z-axis). Easterlies have the greatest range for initial low level moisture/water vapor and a

marginally dry atmosphere can benefit to a small degree from the marginal moisture convergence that occurs from this wind component.

4) WC - WC has the greatest moisture conv. into cells that develop over KSC/CCAFS. Only a limited amount of moisture is required to produce a cell because of focusing of moisture along the SBB axis over KSC. The mean low level initial moisture is also usually high from this quadrant which accounts for a high probability a producing an In-Situ cell with WC steering winds.

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3. Wind Sort for H8H7 Mean Winds

a. Westerly Component (probability of verifying 75% (1987 data) through this portion of the program):

Subroutine:

<u>In-Situ RW</u>

Velocity < 18 kts
KI >= 25.Ø
LI <= -4.Ø
w data >= 15.8/9.7/4.7./N/A
(for each stratified layer)

* if T/O through this portion of program,
T/O all In-Situ.

<u>In-Situ TRW</u>

Velocity < 15 kts
KI >= 3Ø.Ø
LI <= -4.Ø
w data >= 15.8/9.7/5.8/Ø.9

* if T/O through this portion of program,
T/I In-Situ RW real-time mesonet analysis routine;
if no T/O flags through this point,
T/I In-Situ TRW and
RW real-time mesonet analysis routine.

b. Easterly Component (probability of verifying 31% (1987 data) through this portion of the program):

Subroutine:

<u>In-Situ RW</u>

Velocity <= 10 kts
KI >= 28.0
LI <= -3.0
w data >= 16.0/8.0/3.5/N/A

* if T/O through this portion of the program,
  T/O all In-Situ.

<u>In-Situ TRW</u>

Velocity <= 8 kts
KI >= 28.0
LI <= -5.0
w data >= 16.5/9.0/4.0/1.3

* if T/O through this portion of the program,
  T/I RW real-time mesonet analysis;
  if no T/O flags through this point,
  T/I In-Situ TRW and
  RW real-time mesonet analysis routine.

c. Southerly Component (probability of verifying 30% (1987 data) through this point in the program):

Subroutine:

<u>In-Situ RW</u>

```
Velocity <= 10 kts
KI       >= 28.0
LI       <= -4.0
w data   >= 16.0/8.0/3.8/N/A
```

* if T/O through this portion of the program,
T/O all In-Situ scenarios.

<u>In-Situ TRW</u>

```
Velocity <= 8 kts
KI       >= 28.0
LI       <= -5.5
w data   >= 17.0/9.0/4.0/1.5
```

* if T/O through this portion of the program,
T/I In-Situ RW real-time mesonet analysis routine;
if no T/O through this point,
T/I In-Situ TRW and
RW real-time mesonet analysis routine.

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d. Variable Component (probability of verifying 25% through this portion of the program):

Subroutine:

<u>In-Situ RW</u>

Velocity <= 5 kts (by definition)
KI >= 26.5
LI <= -4.0
w data >= 16.0/9.0/3.3/N/A

* if T/O through this portion of the program,
  T/O all In-Situ.

<u>In-Situ TRW</u>

Velocity <= 5 kts
KI >= 30.0
LI <= -5.0
w data >= 17.0/9.0/4.0/1.3

* if T/O through this portion of the program,
  T/I In-Situ RW real-time mesonet analysis routine;
  if no T/O flags through this point,
  T/I In-Situ TRW and
  RW real-time mesonet analysis routine.

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4. Real-Time Forecasting

a. Limiting the Time Window:

The time of occurrence is limited by the amount of available water vapor and the position of the sea breeze boundary (SBB). Graph #1 shows this relationship exists primarily for the EC, VC, and SC wind sectors. The relationship is inversely proportional; as low level moisture increases, less solar insolation is required for showers and thunderstorms to form and therefore they can develop earlier in the diurnal cycle.

Specific Windows When Scenarios Are Active:

1) EC - Active from 09:30L to 13:00L; T/O all other time intervals.

2) VC/SC - Data indicated the two wind sectors were active during the same time periods: 10:15-13:30L.

3) A WC steering wind creates a highly (directional) sheared layer, in the vertical, just above the sea breeze layer which delays convective development until after 11:00L. The window lasts until 14:30L and after that point convection is usually triggered by multiple boundary interaction and not simply from limited convergence along the SBB and such cannot be classified as an In-Situ scenario. 70% of all WC activity occurs between 11:00L and 13:00L and 50% between 12:30L and 13:00L. WC In-Situ activity does not seem to be related to low level moisture, such as the other wind components, aside from a minimum L1 mixing ratio (16.0g/Kg). Apparently, moisture convergence overcomes any relative deficit of low level moisture for convective development. Again WC is active from 11:00-14:30L.

b. Real-Time Sequence of Events: Through this portion of the program, the verification for triggered-in In-Situ scenarios is about 50%. Real-time forecasting will provide the data resolution to change a verification rate from 50% to near 100% for a one to two hour forecast. The foundation for real-time forecasting has to be the mesonet which is reinforced by visual confirmation of the apparent trend that is indicated by the mesonet. A relative sequence of events leading to an In-Situ event is provided within this study to show significance of each individual step as it relates to the verification of the scenario. Data in not available yet, but I feel that as the initial steps of the real-time forecasting routine are verified to exist the probability for the scenario forecast verifying will quickly approach 90-100%. If this is true, the In-Situ scenario could be a solid tool for forecasting In-Situ activity with a high degree confidence. (Time Between Events/Accumulated Time)

1) The mesonet >= -400 unit isopleth sustained for 15 minutes for the maximum convergent value (M.C.V.); usually centered along the SBB (first conformation to the In-Situ RW scenario).

2) Mesonet >= -600 unit isopleth sustained for 15 minutes for the M.C.V.; usually expanding area of convergence along the SBB

(first confirmation of the In-Situ TRW scenario). (+20 min.s/+20 min.s) ???

3) Visual sighting of TCU(s) developing in the maximum convergent area; TCU tops are well defined and "wet". Tops are 10,000 ft to 15,000 ft. (+20 min.s/+40 min.s)

4)

a) Satellite (1 km visual res.) detects 1-3 clusters of bright cumulus indicated over KSC/CCAFS; and,

b) Radar (DAB/COF) indicates the first level 1 DVIP echo located over KSC/CCAFS. (+10 min.s/+50 min.s)

5) Field Mills in the vicinity of the M.C.V. deviate from fair weather fields (+200 to +300 V/m) to <= 0 V/m. This is usually the first non-visual indication that rain is falling at the surface. (+15 min.s/+65 min.s)

6)

a) Visual: Cell has developed into a full fledged cumulonimbus and top is beginning to display an anvil. Cell may show some indications of entrainment at its mid portions but this will not stop the discharge of lightning. If entrainment is present when the cell produces lightning, this is a signal that the cell is already dissipating and is mostly down drafts.

b) Radar (DAB/COF): Radar indicates a circular area of level 2,3, and isolated level 4 possible.

c) Field Mills: Indicate a -1500V/m or less minimum in the area of the M.C.V. . (+10 min.s/+75 min.s)

7) First lightning discharge indicated by:

a) Field mills indicate a positive deviation (> 600V/m) and LPLWS/Field Mills go into the flash routine;

b) LLP indicates a cloud-to-ground strike;

c) Mesonet indicates a strong isopleth gradient between diminishing convergent area and rapidly growing surface divergent pattern which represents the thunderstorm down rush.

c. Note time-line graph #2 for the sequence of events.

d. Dissipation Rates Convection:

1) RW scenario - After the rain begins to fall at the surface (field mills go negative) the average duration of showers is given by:

SC +1:00
EC +1:00
WC + :50 #
VC +1:05

2) TRW scenario - After the rain begins to fall at the surface (field mills go negative) the average duration of the thunderstorm (including rain shower portion) is given by:

SC +2:50 *
EC +1:30
WC +1:25 #
VC UNK (no samples)

* The longest lasting cell was +3:10 from the SC.

WC storm's life cycle is limited due to excessive directional shear which tears the storms apart.

Appendix A: Sea Breeze Progression - Interaction Between the SBB and Thermals over KSC

a) SBB begins moving over CCAFS (about 09:30L)

b) SBB continues inland (about 10:00L)

c) SBB begins to "hang-up" around the heat island area of KSC. Apparent bulge in the SBB progression is caused by transference of sea breeze wind from horizontal to vertical (updrafts). Bulge serves to focus convergence just downwind of the heat island (area of maximum surface temperature measured by the mesonet towers) which enhances cumulus and TCU. (about 11:00L)

d) Sea breeze has almost completely surrounded the heat island/updraft area. Surface maximum convergence value is again just downwind of the heat island and the M.C.V. is down to -600 to -700 units. At this point, the cell has become a CB and supports the greatest amount of liquid moisture and ice crystals of its life cycle (about 12:30L).

e) Sea breeze has re-established itself west of the thermal. In effect, the SBB has over-run the thermal. This destroys the updraft of the cell; relatively cool air is now being sucked in the lower portions of the cell. Also, low level directional shear is helping to dissipate the cell.

Appendix B: Satellite Depiction - Identifying In-Situ Convection Using FL Expanded Visual (1 Km res.)

a) EC example:

1. South of East Quadrant - A cloud line will usually appear downwind of Cape Canaveral proper. As the mixed layer increases downwind the Cape, usually over KSC, a cell will develop along the cloud line and just downwind of the KSC heat island (see satellite pictures 1,2,3).

2. Northeast Quadrant - Favored location for cumulus development is just west of the SLF and west of KSC Headquarters. Normally two distinct cloud elements are detectable on satellite.

b) SC Example: The favored location for cumulus is over northern KSC; north of the SLF-VAB to near PAD 39B. Again, this is the region which has the greatest vertical depth of the mixed layer (see satellite pictures 4,5,6).

c) VC Example: Usually the largest horizontal coverage of cumulus form when steering winds are light and variable. A large area of bright cumulus are usually located over KSC and a cell may develop over CCAFS (see satellite pictures 7,8).

d) WC Example: The WC scenario is the most difficult case to analyze and interpret on satellite imagery. Low level directional shear usually delays the onset of a WC In-Situ scenario, but a WC scenario has the greatest probability of verifying. Most rain shower and thunderstorm activity appears to lean eastward over the SBB indicating a high degree of shearing of storm tilt. This is the reason for the WC scenario being of short duration. This tilting blurs the cell image of the cloud element and makes it difficult to interpret whether the cell is precipitating or not. The mid-portions of the cells will occasionally break-off from the base of the cell located over Titusville. The mid-portion (non-anvil) of the cloud can cause field mill deviations but usually does not cause a lightning discharge. Favored locations for cell development is simply along the SBB. It develops along the immediate coastline (unlike most other In-Situ scenarios) through the Indian River and over the mainland region. Thunderstorms can develop rapidly from rain showers and also dissipate rapidly. Thunderstorms tilt eastward over the SBB just as rain showers do and are surrounded by a great deal of random cloud debris. The only distinguishing feature for these thunderstorms is that they have a greater diameter than the other cloud elements located along the SBB and they are slightly more bright. Generally, once the satellite can identify a developing thunderstorm along the SBB that may threaten KSC/CCAFS, the horse is already out of the barn. A better method for Met-Watching such conditions is:

1. Knowing there is a strong probability for an In-Situ cell to develop; and,

2. Monitor the cloud visually on a real-time basis; keep an eye on the mesonet and field mills; numerical data displayed at the Forecast Facility (mesonet, field mills, other statistics) must be initialized visually before a forecaster commits himself/herself to a forecast (see satellite pictures 9,10,11).

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Appendix C: Error Analysis

a) As many will point out, this was a bare bones research project and only 2 1/2 months of weather observation was included in this report. During the 2 1/2 months, there were:

12 WC samples
4 EC samples
3 SC samples
2 VC samples
----
21 total samples.

This is certainly not enough climatology to base a forecasting program on. Using the framework of this study, future studies on the In-Situ phenomenon should add data to, and strengthen, this study. Information from ETAC may be useful to archive data from previous years, but I don't think the information would be detailed enough for a comparable addition to this study. In other words, the presence of the experimenter during data collection is critical when evaluating and classifying the data after-the-fact.

b) Moisture, KI, LI, wind velocity, and timing of convection information used to classify the individual scenario was evaluated separately for each piece of data. Most data were analyzed and collected by hand, increasing the probability for human error. This error was reduced by subsequent re-evaluation of the data on a case by case basis. Between Mr. Smedley and myself there exists almost 30 years of experience dealing with exactly the same basic data that was used throughout this study.

1. Moisture was probably the most subjective data derived from the basic information. An equal-areas method was used on the mixing ratio for a specified layer. The error for this parameter may include equipment error (from the rawinsonde itself), and human error through plotting and analysis.

2. The steering winds may be too high (vertically) to gage moisture convergence occurring at the intersection of the SBB, especially for the WC scenario. Steering winds (mean winds 850mb through 700mb) were averaged and may be subjective to a small degree.

c) Human Error Summary: For such a small sample group, there normally should be some concern that human error may contaminate the data. I feel the care that was used during the collection and analysis of the data reduced the human error to a negligible amount.

d) Other complications that occurred during the data collection were data holes that were caused by the inability to observe and/or analyze an event. This arose for many reasons:

1. A large problem that limited the experiment was the inconsistency of the mesonet. The total area divergence data was useless because of data loss within the network. As much as we could, we monitored the maximum convergent value which was largely unaffected

by data loss west of the Indian River. This too was inconsistent due to Cyber central computer processing problems created by an operating system switch over which took fully two months to accomplish. To gather convergence data, the technician had to copy information as it was displayed on the video CRT, as we were limited only to real-time access to the data when it was available. The problems with the mesonet were probably the most disappointing and frustrating problems for the experimenters. For this reason, the convergence values used in this report are "ball park" numbers that we were able to obtain in only 20% of the In-Situ events which is not enough to establish forecasting criteria. This area is certainly ripe for further analysis as it relates to In-Situ activity.

2. Field mill data were more consistent than mesonet data, but once again we were only able to access real-time data and had to hover over the video presentation as it was displayed to get a hard-copy for further study. Once again, field mill information contained within this report is based on a few data samples and should be studied further.

3. Limits on Visual Observations:

a) Visual observation of cumulus development was part of the foundation of this study. From the southwest corner of the CIF, we had a field of vision from 090-180-270-360 degrees. This meant that we were blind in the northeast quadrant. This area included the PAD 39A/B and complex 40/41. Frequent trips down the hallway to a point where the northeast quadrant was visible helped to close this blind spot, but it probably did reduce the In-Situ sample number and throw-off the onset/dissipation of activity in that region

b) Time Constraints: The technicians would never leave the Weather Lab during the period when an In-Situ event was taking place. Many times I would come back from a brief lunch or meeting only to find an In-Situ event in progress, causing me to estimate the onset of the event. On rare occasions, the Weather Lab was not manned all day and again we potentially could have lost valuable case-studies.

c) Because the study had some periods when data collection was limited, the number of possible In-Situ cases should be slightly larger than indicated within this report for the period of the report. This indicates that In-Situ convective activity may occur on up to 40% of the air mass regime days, which is a much higher figure than most forecasters imagine occur. Whether or not some of the activity classified as In-Situ events are operationally significant is irrelevant. This study set out to forecast 100% of the showers and thunderstorms that develop over KSC/CCAFS. In the event the Shuttle should ever attempt to land back at KSC, I believe the detail with which this report was prepared will be useful when preparing a forecast.

Appendix D: Definitions

a) Moisture Layers:

L1 = Layer averaged mixing ratio surface to 900 mb

L2 = Layer averaged mixing ratio 900-750 mb

L3 = Layer averaged mixing ratio 750-600 mb

L4 = Layer averaged mixing ratio 600-400 mb

b) Steering Winds (H8H7): The mean wind direction and velocity from 850 mb to 700 mb.

c) In-Situ Rain Showers/Thunderstorms: The occurrence of convective activity over KSC/CCAFS proper without the cell forming outside KSC/CCAFS boundaries and advecting over KSC/CCAFS; in other words, the cell must form over KSC/CCAFS. Trigger mechanisms are limited to sea breeze convergence and associated terrain induced focusing of the sea breeze by Cape Canaveral proper and thermals which form over the land area of KSC/CCAFS.

d) Data Resolution: The ability to formulate a forecast from raw data that can predict whether In-Situ activity will form and what will be it's intensity if it does form.

Appendix E: Overcoming Data Limitations and Quality Control of the XMR Rawinsonde Data

a) No Upstream Data (steering winds from the east-northeast): Forecaster must integrate the water vapor loop into the data analysis to determine whether XMR's morning rawinsonde will be valid through the afternoon diurnal cycle. If the water vapor indicates an impending change in the moisture profile, the forecaster must amend the forecast to reflect that change.

b) Quality Control: The XMR Skew-T data must be checked against upstream Skew-T information if available. Changes due to thermal and moisture advection should be included in the front-end analysis.

c) If the above controls are used the data base should be valid through the forecast valid time. Failure to include upstream data in the front-end analysis will reduce verification rates. Advecting upstream data over XMR during the forecast valid time is the only way to overcome the static character of the program.

D R A F T

Appendix F: Raw Data

June 1987

Date	Moisture L1/	L2/	L3/	L4	H8H7 WND	KI	LI
1	14.0	6.9	1.0	0.4	09010	2.9	+1.0
2					10010	1.3	-1.5
3	15.0	7.3	1.4	1.4	08010	6.4	-3.1
4	14.2	6.6	4.1	1.3	06005	15.1	-3.4
5	15.8	7.5	6.2	1.9	05005	25.0	-6.0
6	16.0	10.0	6.6	2.5	05005	34.3	-5.0
7	13.0	9.5	2.2	0.7	08010	11.3	-1.8
8	12.5	5.2	2.0	0.8	09010	10.3	-1.5
9	14.1	5.0	1.3	0.6	11007	11.3	-4.0
10							
11	15.0	9.7	3.0		17005	31.5	-5.0
12					10010	31.2	-3.1
13							
14	15.2	11.5	6.3	1.8			
15							
16	17.8	13.5	5.5	0.4	19007	29.0	-4.2
17	16.0	12.0	4.7	0.9	24008	27.0	-5.0
18	15.0	11.0	4.0	1.4	14008	36.0	-6.0
19	18.5	6.0	3.3	2.5	15006	31.0	-9.0
20					14008	10.0	-5.0
21	15.8	8.2	3.4	3.3			
22	18.0	13.0	3.8	2.1	18008	28.1	-6.2
23	19.0	12.5	7.2	2.6	22008	19.0	-7.5
24	17.8	11.9	7.5	1.5	26012	27.5	-5.2
25	18.3	12.0	6.9	1.7	26015	33.8	-8.3
26	17.8	10.5	7.3	1.8			
27	18.1	12.1	7.8	3.3			
28	16.1	10.3	6.9	3.2			
29	14.8	11.2	7.8	3.6	26006	34.5	-2.0
30	18.0	11.9	7.7	4.3	17010	38.4	-1.0

NOTE: H8H7 WNDS > 10 KTS DISREGARDED UNLESS AN IN-SITU EVENT OCCURRED ON THAT DATE.

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July 1987

Date	Moisture L1/	L2/	L3/	L4	H8H7 WND	KI	LI
1	17.9	9.0	3.9	1.7	13010	28.9	-6.0
2	15.9	12.2	7.0	3.0			
3	16.5	8.4	5.2	1.4			
4	17.0	10.5	5.3	1.3	20008	30.6	-6.5
5	15.5	9.5	4.0	1.8	14006	30.0	-5.0
6	18.0	11.3	5.3	1.6	11006	35.4	-8.0
7	18.0	11.4	4.5	1.1	17003	26.8	-8.2
8	16.5	10.0	4.5	1.4	06007	28.6	-6.2
9	16.2	8.8	5.1	1.5	06008	27.2	-6.2
10	16.0	9.0	4.7	1.3	09008	25.3	-6.0
11					05004	19.3	-4.7
12	17.7	10.9	3.7	1.7	27007	26.5	-6.3
13	13.7	7.8	5.1	1.2			
14	17.0	11.7	5.8	2.1	29007	34.0	-8.7
15	17.9	11.5	6.4	1.5			
16	15.8	10.9	5.9	1.4	25011	32.3	-4.0
17	14.8	11.8	5.8	0.4	20007	35.5	-4.2
18	17.0	11.4	6.3	2.0			
19	15.9	9.5	6.0	2.0			
20	17.0	10.4	6.9	3.0			
21	19.0	13.0	5.1	0.8	08008	39.2	-7.5
22	15.9	3.8	1.5	0.7			
23	15.4	6.6	2.8	0.6			
24	16.7	8.2	2.2	1.1			
25	16.0	9.0	2.0	0.6	27003	27.5	-5.0
26	16.8	10.9	5.8	1.9	21007	30.5	-5.0
27	16.0	9.7	6.0	0.9	21007	31.9	-6.0
28	16.0	11.5	5.1	1.8	23007	36.0	-6.0
29	17.0	11.7	6.4	3.8			
30							
31	16.0	12.0	7.3	2.9			

NOTE: H8H7 WNDS > 10 KTS DISREGARDED UNLESS AN IN-SITU EVENT OCCURRED ON THAT DATE.

D R A F T

August 1987

Date	Moisture L1/	L2/	L3/	L4	H8H7 WND	KI	LI
1							
2	15.6	11.0	6.1	1.5			
3	17.8	11.0	6.6	2.0	21008	32.4	-3.0
4	17.8	12.0	7.0	1.5	21008	30.2	-4.5
5	18.0	11.1	6.8	1.8	21008	28.3	-5.6
7	17.7	8.4	3.2	0.8	15008	22.3	-7.0
8	14.5	5.9	1.8	0.7	27004	11.1	-2.8
9	17.8	13.1	5.1	0.9			
10	17.3	11.2	6.0	0.8			
11	16.5	12.0	6.6	1.2	36017		
12	17.0	12.0	7.3	2.8	31004	32.4	-4.0
13					27014	32.8	-6.0

NOTE: H8H7 WNDS > 10 KTS DISREGARDED UNLESS AN IN-SITU EVENT OCCURRED ON THAT DATE.

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Scenario-Driven Automatic Pattern Recognition in Nowcasting

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ABSTRACT

The purpose of this paper is to illustrate how the construction of a knowledge-based system (KBS) to support nowcasting, can be used to guide and facilitate the development of objective pattern recognition algorithms for use with meteorological data. We believe that a KBS based on the semantic interpretation of weather data, using the concept of weather scenarios, can assist the development and use of objective algorithms for pattern recognition in two ways:

1) it focuses the development of pattern recognition algorithms on only those phenomena which are most useful to operational forecasters;
2) its top-down logic constrains when, where, and how objective algorithms should be applied.

We first describe our understanding of nowcasting expertise and the use of pattern recognition ("manual") by human forecasters. We then briefly review the current use of automatic pattern recognition in nowcasting, present the elements within a scenario and discuss a KBS architecture for using scenarios. Finally, we close by discussing the practical benefits of merging a qualitative KBS with algorithmic pattern recognition techniques.

1. The nature of nowcasting expertise

The ideas in this paper stem from an ongoing project to develop a KBS to support nowcasting at NASA's Kennedy Space Center (KSC). Most of the knowledge engineering effort has centered on identifying and characterizing the nature of the expertise of two forecasters, each with over 15 years of experience in forecasting weather at KSC. Additional interviews have been conducted with a dozen forecasters whose experience at KSC ranged from 3 months to 3 years.

We believe that the modus operandi of expert nowcasters is to build or select one or more mental models of a given weather situation by matching past experience to current observed features. These models are used as guides in identifying and tracking individual patterns in available data sources and then both to extrapolate forward very short-period events, and to predict the likely evolution of the current mesoscale system on the basis of similarity to past situations (Schlatter, 1985).

When asked to describe these models, expert forecasters typically relate them as short stories, describing the development of a complex weather pattern. Typically, a number of experiences will have been summarized into an abstract story which the forecaster then uses as a guide in observing and interpreting new weather situations. We have termed these dynamic abstractions "scenarios" to distinguish them from the more static historical records of weather events and from "scripts" in the sense understood in the artificial intelligence (AI) community (Shank and Abelson, 1977).

Expert-level nowcasters appear to depend heavily on the use of weather scenarios which characterize generic classes of weather patterns and their development over time. Scenarios are used by expert forecasters to define the range of possibilities for how the weather will evolve over the next several hours. At any one time, forecasters may use several competing scenarios to guide them in developing a forecast.

Weather scenarios have a direct parallel in the "conceptual models" discussed by Brown (1985). According to Brown, conceptual models describe typical configurations of air flow, temperature and moisture. Similar to scenarios, the primary use of conceptual models lies in the interpretation of multiple data sources, and the assignment of specific weather phenomena to particular geographical regions. Scenarios, however, are explicitly concerned with the configuration and evolution of mesoscale patterns previously observed at KSC.

2. Pattern recognition and scenarios

A scenario can be thought of as a multidimensional hypothesis that describes the expected patterns of change in various weather systems across a varying number of meteorological data streams or sets.

Selecting a particular scenario as a good analogy of how today's weather might evolve requires a complex pattern identification and matching process. At least four separate levels of pattern recognition appear to be involved:

• Recognition of individual patterns or features *within a data set.*

• Recognition of clusters of related features *across data sets.*

• Fusion or differentiation of *features* within a data set *across time.*

• Recognition of patterns of change in clusters of related features *across time.*

The dynamics of meteorological phenomena add a level of complexity not normally found in pattern recognition tasks. In most high-level pattern recognition problems (such as scene identification), the properties of the objects are fixed. Even if the scene is a dynamic one, the moving "objects" do not change their intrinsic properties of shape, albedo and so forth at any significant rate. However, identifying a meteorological system is *not* just one of identifying a collection of objects but one of identifying a *process.* The individual entities in the scene (e.g., localized storm cells, clear areas, convergence zones) evolve and give only clues to the processes involved but do not themselves constitute that process. Two weather situations which are the same, in terms of the processes involved, can appear as being very different when viewed as collections of individual weather elements. These considerations become critical when the aim is to track the evolution of short-lived weather elements over most or all of their life cycle.

3. The problem for automatic pattern recognition

In a modern forecasting environment, such as that provided by a PROFS or McIdas workstation (Mandics and Brown, 1985; Schlatter, 1985), the forecaster is deluged by the sheer quantity of data which is available. It is physically impossible for a forecaster to examine all of the data, yet somehow expert forecasters cope quite well. Inexperienced forecasters, on the other hand, are frequently at a loss to know precisely where to focus their attention.

We believe that one of the primary differences between expert and novice forecasters in such a data-intensive situation is that expert forecasters are *selective* in the data they choose to examine. Experts appear to ignore the majority of data and concentrate only on that which is *currently* most meaningful. In other words, they effectively use their knowledge and experience to guide them in deciding what subset of data to analyze. This can be thought of as a top-down approach in which top-level scenarios guide the expert in selecting data and features to examine.

In contrast, the typical approach to developing and using automatic pattern-recognition algorithms has been bottom-up. A set of processes is developed which identify any and all features that might be of interest in a data set, and aggregate them into any and all objects of potential interest.

Given the number of sensor systems available in a modern forecast facility and the significant computational requirements for most pattern recognition algorithms, it is nearly impossible to automatically identify every feature of potential interest in all data sets or streams. Even if it were possible, it is not clear that the forecaster could use all of the output because of the overwhelmingly large number of features available.

An expert human being, on the other hand, determines what patterns and features are of interest *before* doing any detailed analysis of hard data. We believe this selection is governed by which scenarios the expert has selected as potential analogies for today's evolving weather patterns.

Our thesis is that scenario descriptions can guide in the selection of which data should be used, which algorithms should be applied, and when the analyses should be conducted. Such an approach should allow automatic pattern recognition to replicate the expert human's selectivity in the face of too much data. We are using the scenario structure to describe the meteorological process. Scenario recognition is peformed by matching the scenarios to today's situation using global scene descriptors (such as overall synoptic flow, presence of local cells in different regions relative to the synoptic flow and existence of local convergence zones).

4. Status of pattern recognition in nowcasting

There are currently three areas of automatic pattern recognition in support of nowcasting operations:

1) derivation of inferred meteorological fields;

2) identification of individual meteorological features; and

3) tracking of individual meteorological features.

Inferring significant meteorological fields from observed data is perhaps the most advanced of current applications. In some cases there is a direct physical connection between the desired field and the observable data (for example, derivation of rainfall rate from radar reflectivity by use of a raindrop spectrum) in which case the procedure can be carried out purely algorithmically with recourse to recognition techniques. However, many times there is no simple physical relationship which can be used as the basis for a purely analytic solution, and statistical procedures must be used which deduce the desired field from weakly related observables.

This simple use of pattern recognition is equivalent to the image processing task of labeling pixels on the basis of purely local information. It provides the user with field information such as "there is a high rainfall signature is this local region" but does not specifically identify localized objects of meteorological significance. This local identification of signal patterns can be the first step in more sophisticated pattern recognition, and can also be a meteorological product for direct use by forecasters.

The second major role for automatic pattern recognition is the more complex one of actually identifying individual, meteorologically significant events. This corresponds to the segmentation and object-labeling phases of image processing systems. Typical entities of interest might be:

- region identification (sea, land, type of cloud cover) from satellite data
- wind shift boundaries (from doppler radar)
- storm cells

See Roska (1985) for an example of this type of pattern recognition.

The final role for automatic pattern recognition in current practice is the tracking of the features identified above, either for purposes of extrapolation forecasting (e.g., tracking storm cells), for prediction (e.g., looking for future intersections of wind shift boundaries which could lead to initiation of new cells) or for inferring indirect information on the bulk fluid flow.

The foregoing processes may be considered as a bottom-up flow from raw data streams to semantic-level interpretations. A simplified picture of this situation is shown in Fig. 1. Here the raw signal is first preprocessed to validate the data and peform basic noise reduction. Geometric transformations are also applied at this stage to map the data into a standard coordinate frame.

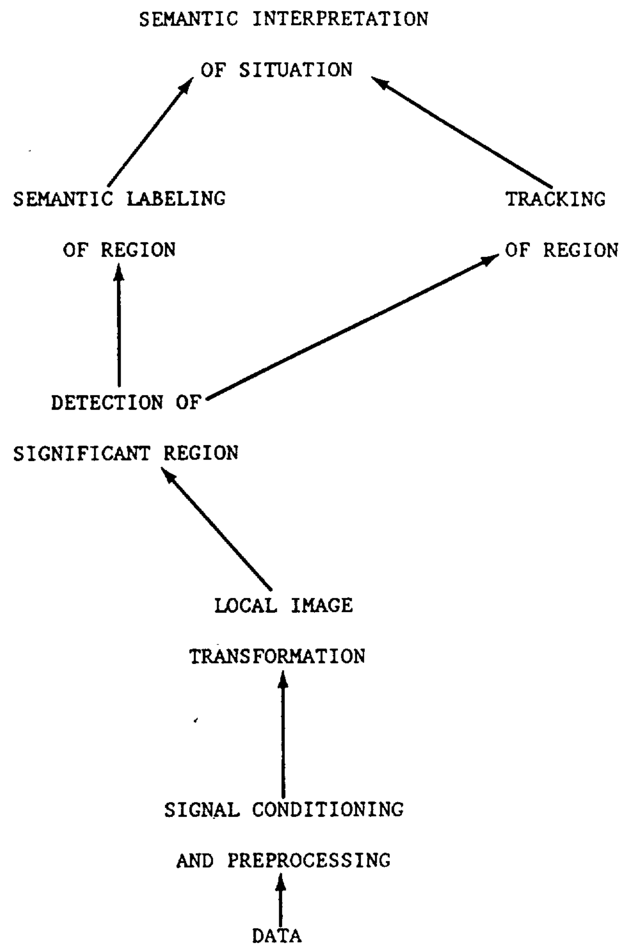

FIG. 1. Simplified sequence of processes involved in performing a pattern recognition task in nowcasting.

Three of the layers in Fig. 1 correspond to the three pattern recognition roles noted previously:

1) local transformation and labeling;
2) delineation of significant "objects" or regions within the data;
3) tracking of regions (possibly involving recourse back to unsegmented data).

Two final stages are required: semantic labeling of the individual regions and semantic interpretation of the complete weather situation. It is the encoding and application of this semantic knowledge that is addressed by the use of the scenario structures.

As long as no hypothesis is being used to guide the process (as is the case in all current nowcasting workstations) then the data flow has to proceed purely bottom-up as previously described. However, once a complete path exists up to a semantic interpretation it then becomes possible to run the interpretation graph top-down and use the established interpretation to

1) guide in the selection and application of lower-level processing and to concentrate the available computing resources on the important regions and phenomena;
2) provide a context in which to validate low probability identification and reduce false alarm rates (at the risk of detecting only what the high level interpretation expects to detect!).

While the major data sets in use are from satellite and radar imagery, our aim is to interpret the complete meteorological situation, including all the other standard data sources within the interpretation: mesoscale networks, vertical soundings, hourly surface observations, field mill and lightning detection data.

5. Scenario structure

The current formulation of scenarios consists of a four-tiered hierarchy of data types, shown schematically in Table 1. The scenario level represents the highest level of abstraction. Lower levels of abstraction occur with lower rows. The order of procedural control when processing these data structures in a KBS proceeds from scenarios down the hierarchy. The four basic data

TABLE 1. Principle attributes for the four data types used to model the various levels of abstraction required to perform the pattern recognition task in Fig. 1.

Data types	Attribute type: Static	Attribute type: Dynamic
Scenario	Events: ordered list, dependency constraints; Assumptions: necessary, sufficient; Rules of thumb	Status; History
Event	Predicates	Scenario; Status; Associated features; Dependency constraints; Monitoring window; Time stamp
Feature	Associated variables; Pattern recognition algorithms; Observation interval; Climatology	Events; History: status, location, size
Variable	Measurement function	Value history; Magnitude; Direction

structures are represented as schemas or frames within an inheritance mechanism which allows a taxonomic description of the attributes (i.e., slots) that define the characteristics of each data structure. For more information on frames and schemas see Minsky (1975), and Fox (1979) and Winston (1984).

At the bottom of the hierarchy lies the *variable,* which usually consists of time-value pairs. The *feature,* in turn, is an identifiable weather entity, ranging in complexity from a steering level wind to an individual thunderstorm cell, described by certain variables. An *event* is a qualitative change in some feature, and occurs at a specific point in time. Finally, a *scenario* is composed of multiple events, as well as the dependencies between those events.

Each data type is defined by referencing the next-simplest data type. Events, for example, are defined as changes in features, while features reflect patterns in particular variables. Thus a scenario, which directly refers only to a set of events, indirectly depends on the definitions of features and variables which underlie those events. Table 1 also gives examples of the two types of attributes required to define each data type. Static attributes are those which are a part of a data type's primitive definition, and remain constant over the lifetime of any specific object. Dynamic attributes, will change over time as conditions change and more becomes known about a specific object. The distinction between static and dynamic attributes is a useful one, since static attributes are all that is required when defining objects residing in a permanent knowledge base, while dynamic attributes are those of interest to the forecaster when performing a problem-solving task.

Variables are relatively simple. In addition to a value history, variables typically also have indicators for their current magnitude, direction and rate of change. Methods for obtaining measurements are associated with each variable; such a method might reference a particular type of accessing function into a data base, for example, or might simply "ask the user."

Features represent weather entities with identifiable behavior. A feature corresponds approximately to something which an operational forecaster might refer to as "it" in common speech: a "cell", "sea breeze" and "frontal zone" are all examples. In addition to a list of associated variables, a feature requires a history of its status and location, and an observation interval, the length of time between observations. A feature may also have a climatology which describes statistical aspects of its historical behavior.

Events are qualitative changes in a specific feature, or by extension, a group of features. To simplify the process, an event is assumed to occur at an instant in time rather than over a finite duration; this allows an event to have a time stamp indicating exactly when it occurred, or was observed. An event also has a predicate, which is a statement that can be tested (i.e., quer-

TABLE 2. Definitions and explanations of various modules in knowledge-based scenario system in Fig. 2.

Module	Description
Detect	Using future expectations as a guide, gather data and update the current set of features being tracked.
Anticipate	Based upon the current state of all active scenarios, generate a set of expectations about the future.
Monitor	Compare current conditions with expectations and modify the list of active scenarios accordingly.
Edit	Editing and composition facility for building the knowledge base.
Data	Description
Data base	Conventional data base of meteorological observations.
Expectations	List of events (with specific monitor windows) being actively watched.
Today	List of features identified during the recent past, each of which has its own history, etc.
Activated scenarios	List of scenarios being actively monitored.
Knowledge base	Static definitions for all scenarios, events, features and variables used by the system; also a body of productions rules for testing predicates.

ied) as to whether or not it has already occurred (Kowalski, 1979; Clocksin and Mellish, 1980). Such a predicate may be considered a top-level hypothesis which, when discovered to be true, proves that the event has "happened." In addition to its predicate, an event has a monitoring window which contains the time period during which the event is expected to "happen." Various actions are typically taken depending on whether an event "happens" before, during or after its monitoring window.

A scenario is defined by an ordered list of events and dependencies between those events. Simple event dependencies take the form of

[event-1 (time-1 time-2) event-2]

which translates as "event-2 should happen between time-1 and time-2 after event-1" where time-1 and time-2 are time intervals (expressed, for example, in number of minutes). The list of event dependencies defines a highly constrained temporal sequence which is analogous to, but much more general than, the event chains and fault trees used in operations research (Taha, 1971); they are similar in many ways to the various types of event chains as discussed in the AI literature (McDermott, 1985).

In addition to the events and their dependencies, a scenario also requires a set of assumptions, both sufficient and necessary. Typically these assumptions are statements which may be queried in the same way as event predicates. Scenarios are tested to see if they should be activated by periodically querying their sufficient conditions; once activated, their necessary conditions are periodically queried to ensure that they are still worth monitoring.

6. Scenario processing

The architecture of the KBS is intended to model to a considerable degree the way we believe expert nowcasters use scenarios. Figure 2 shows the major modules and data flow within the KBS. Table 2 contains definitions of module functions. The top-level functions in Fig. 2 are "monitor," "anticipate" and "detect". The editing facility initially is an off-line facility for working on the knowledge base of scenarios. The monitor function is reponsible for monitoring the ongoing weather events of today and activating or deactivating scenarios as appropriate. Anticipate works off of the activated scenarios to generate predictions or expectations of future weather events. The detect function translates the expectations into requests for specific data or analyses and schedules the requests appropriate to the observational intervals and the monitoring windows. Each top level box can be expanded, but the details are beyond the scope of this paper.

We view this architecture as providing a means for capturing the reasoning and experience of forecasters at a high level of abstraction. It is qualitative and symbolic, and is exclusively concerned with the logic and structure of forecaster expertise. The architecture is also semantic, in that it describes and interprets weather conditions in much the same way as a human forecaster.

Pattern recognition algorithms, on the other hand, attempt to capture the detection and tracking of me-

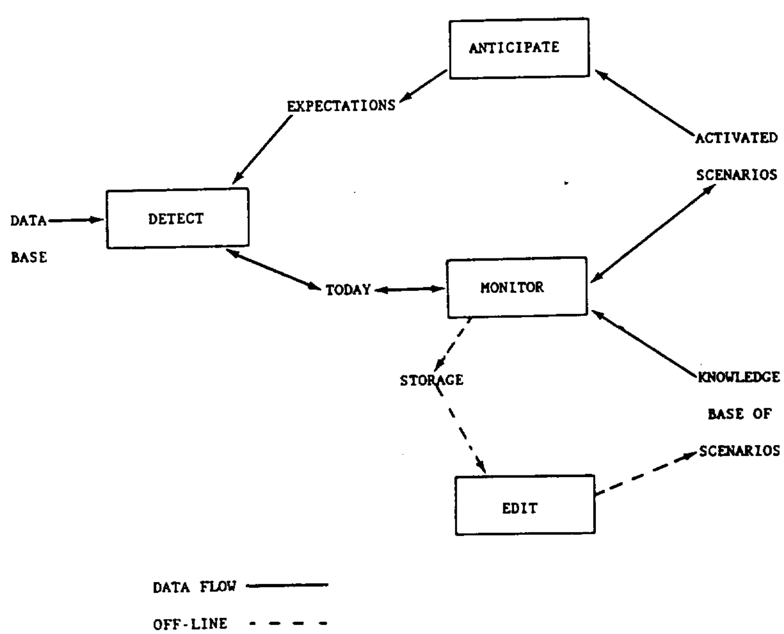

FIG. 2. Top-level description of important modules within knowledge-based system for use by nowcasters at Kennedy Space Center.

teorologically significant features in a quantitative manner. Typically, the thought processes and reasoning strategies of the human forecaster are of little interest, except as a general guideline to how pattern recognition might be completely automated. Moreover, an objective algorithm for pattern recognition almost never contains a mechanism for incremental improvement of the algorithm, other than parameter reestimation.

7. Scenario-driven automatic pattern recognition

It is our belief that practical considerations argue for the parallel development of qualitative nowcasting KBS and objective pattern recognition algorithms. We believe this for two reasons:

1) The modeling of forecaster expertise can guide the search for algorithms which are most useful to operational forecasters;
2) The top-down logic of a KBS, particularly the use of scenarios, greatly constrains when, where, and how objective algorithms should be applied.

Given the range of possible patterns which could be detected automatically in meteorological data, the first reason is fairly obvious. That is, there is an extremely large number of patterns which could be analyzed objectively, and a large number of data sets or streams in which to search for them.

By delving into the logic of forecaster reasoning, it is possible to uncover those types of features which are the most important to the forecaster and define what sorts of information should be provided about those features. The development of automatic algorithms for pattern recognition should also take into account the task-related needs of the forecaster by considering the worst-case combinations of weather, time pressures and data overload. There is little point, for example, in providing sophisticated algorithms for tracking isolated storm cells if the most pressing operational problems are caused by simultaneous monitoring of surface winds, precipitation rates and lightning frequency.

The second reason for parallel KBS and algorithm development has more to do with how algorithms are applied at run time. A KBS which uses top-down logic to find "interesting" scenarios and events to monitor can provide a powerful set of constraints concerning the use of objective analysis.

Once a symbolic model of the situation has been selected and instantiated by choosing a suitable scenario, the problem becomes one of monitoring the evolving situation both to check that the model is correct and to forecast the weather. This consists of looking for the appearance of individual events (onset of sea breeze, development of local convergence zone, development of storm cell complex) and the tracking of these events (tracking storm cell and extrapolation to predict future path and evolution).

The scenario also will indicate the geographical locations and times where the most important events are likely to occur. Thus the scheduling of computing resources to look for such events can be based on this expected likelihood and importance. A concrete example of this is the interpretation of synoptic flow to infer those regions where storm cell formation is important and to concentrate processing largely in just those regions.

The deployment of automatic pattern recognition resources will be determined by the particular set of dependency constraints between events, the set of monitoring windows across events, the observation interval for each feature within an event, the particular pattern recognition algorithms associated with each nested feature, the area in which the feature is expected to be found and the particular data-set or stream.

Given these constraints, improved efficiency can also result from selection of algorithms by compute-intensiveness. For example, a relatively inexpensive algorithm might be used early in the unfolding of a scenario when false positives might not be a problem. Then more expensive algorithms could be used to validate the occurrence of an event.

It would be possible to utilize algorithms which are more compute-intensive, on a pixel-by-pixel basis, because the algorithms will be applied in a highly selective manner. It is also possible to contemplate a much wider range of algorithms than would otherwise be possible, since only a small subset of all available algorithms will need to be applied at any one time.

A scenario-driven automatic pattern recognition scheme would have a number of implications for the pattern processing systems. A large library of algorithms would have to be available either in software or as programmably reconfigurable hardware. Both of these trends can be identified presently within the machine vision and pattern recognition industries.

The scenario structure would make the implementation of a parallel architecture relatively easy because each measurement function, algorithm call or event predicate can be handed off as an asynchronous task. Again, parallel systems architectures are beginning to appear in AI machines and in proposed machines combining AI and image interpretation.

This structure also means that the development of the KBS can proceed ahead of the development of automated pattern recognition systems, because each task can also be handed off to the forecaster for detection and/or measurement.

The advantages of a scenario-driven system are bought at the risk of detecting unexpected events somewhat later than they could have been under a purely bottom-up recognition scheme. This is, in any case, the price paid by humans with their expectation-driven view of the world. We can only strive for a compromise which allows a suitable trade-off in wasted computing power against the risks of failing to see the unexpected.

8. Future directions of nowcasting KBS

During the first phase of development, the nowcasting KBS domain has been restricted to summertime thunderstorms. The scenario structures are precompiled and not modifiable at run-time. They are either active or inactive.

Subsequent phases will extend the domain of the system to year-round weather phenomena and will incorporate a dynamic scenario modification system so that a variation on a given scenario can be constructed during run-time based upon partial matches to existing data. Such an extension could begin to incorporate some elements of causal modeling (Bobrow, 1985; Hayes, 1979).

Future extensions could incorporate a facility whereby new scenarios were automatically generated by the system based on symbolic descriptions of today's actual weather events. Such a system implies a well-understood vocabulary of symbolic descriptors and an extensive taxonomy of scenarios (among other things).

Additional types of knowledge could be included as part of the scenario selection process. For example, the launch of a shuttle orbiter is accompanied by a large number of weather constraints. Given those constraints, scenarios could be monitored which have events outside NASA guidelines which could occur within the launch window.

9. Summary

We urge the use of a KBS architecture which employs a semantic interpretation of current conditions to govern, in a top-down fashion, the execution of objective algorithms. We envision that such an architecture will imply the need for algorithms which are considerably simpler than those needed in the absence of semantic information. On the other hand, there will likely be a greater variety of algorithms required, since they largely will be specialized to handle the detection and monitoring of very particular types of meteorological features. We firmly believe that the combination of qualitative and quantitative knowledge in such a hybrid system will be far more powerful (and useful!) than the current generation of support tools for operational forecasters.

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